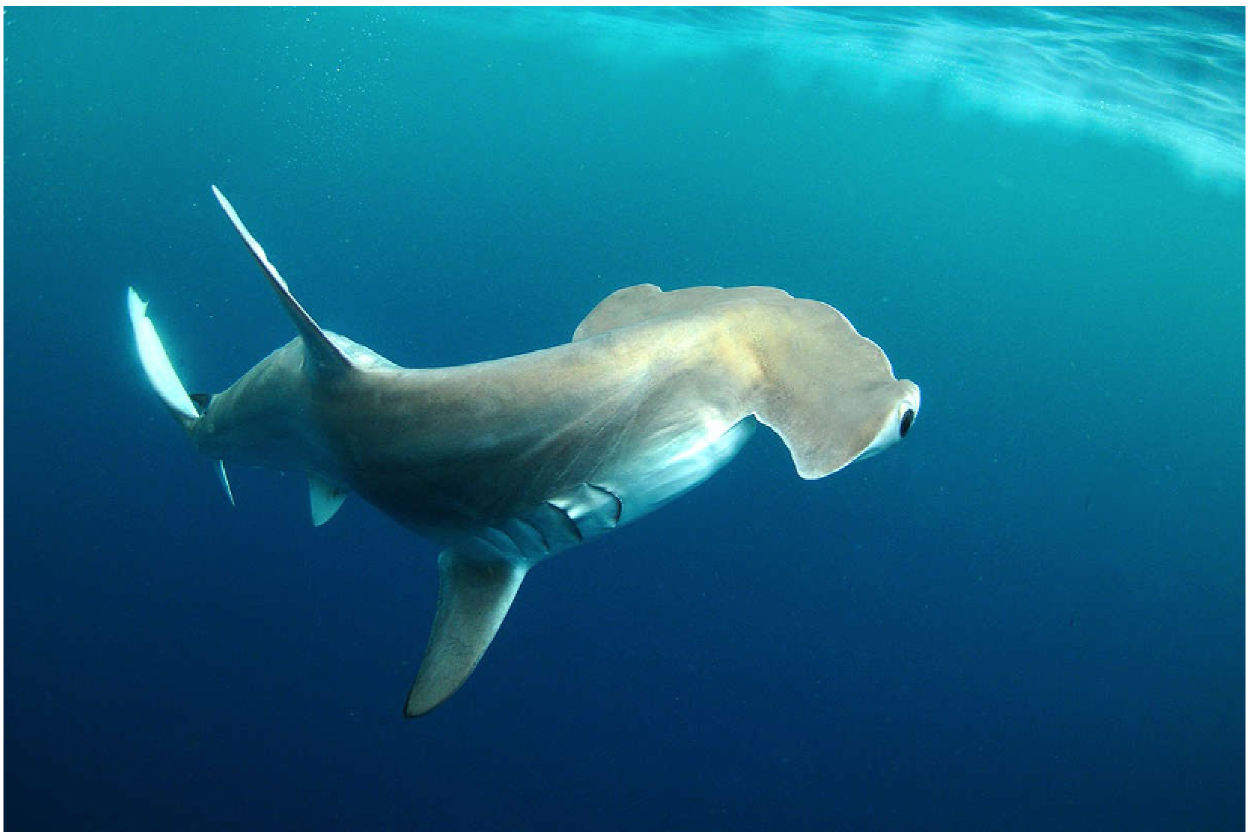
A Framework for Designing Marine Protected Areas for Shark and Rays in Mozambique

Anna Abelman, Courtney Krone, Vanessa Rathbone, Rachel Rhodes, Erin Ristig



Advisors: Dr. Hunter Lenihan & Casey O'Hara

Client: Wildlife Conservation Society

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X
Anna Abelman

X
Rachel Rhodes

X
Courtney Krone

X
Erin Ristig

X
Vanessa Rathbone

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X
Hunter Lenihan

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Abbreviations

BLM	Boundary Length Modifier
BRUV	Baited Remote Underwater Video
EEZ	Exclusive Economic Zone
CCPs	Comunitários de Pesca
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CMS	Conservation of Migratory Species of Wild Animals
GDP	Gross Domestic Product
KBA	Key Biodiversity Area
IUCN	International Union for Conservation of Nature
MPA	Marine Protected Area
REPMAR	Regulamento da Pesca Marítima
UNEP	United Nations Environment Programme
VMS	Vessel Monitoring Information
WCMC	World Conservation Monitoring Centre
WCS	Wildlife Conservation Society

Abstract

Chondrichthyes, a class of marine cartilaginous fish (sharks, rays, skates, and chimaeras), are important predators in pelagic, coastal, and estuarine food webs. Many of these species are at high risk of extinction with approximately one-quarter of sharks and rays categorized as threatened according to the IUCN Red List. Mozambique is a global hotspot for shark and ray species richness, endemism, and evolutionary distinctiveness. Chondrichthyes face many threats in Mozambique, especially from fishers, as up to 60% of the population is in some way dependent on marine resources for either sustenance or employment. Marine protected areas (MPAs) may be an effective conservation strategy for sharks and rays if carefully planned. Here, we develop a spatial prioritization model that identifies key areas for shark and ray conservation within the Mozambique economic exclusive zone (EEZ). This is an intermediate step in an ongoing MPA planning process currently underway in Mozambique. Our model will be used by Wildlife Conservation Society (WCS) and the Mozambique government to ensure shark and ray protection is considered in the overall MPA network design.

Executive Summary

Objective

The goal of this project is to ensure the long-term persistence of sharks and rays within the Western Indian Ocean through an expanded network of marine protected areas in Mozambique. Our client, Wildlife Conservation Society (WCS), is working with the Mozambique government to improve the management of these species through a National Plan of Action for shark and ray conservation, as well as a strategic expansion of Mozambique's existing marine protected area (MPA) network. Our project will contribute to their efforts by: (1) developing a reproducible spatial model that identifies priority areas for the most at risk shark and ray species in the Mozambique Channel, and (2) providing recommendations based on this model for a network of protected areas specific to sharks and rays that can be incorporated into the greater marine protected area planning process.

Background

Over one-quarter of all shark and ray species are threatened with extinction according to the IUCN Red List (Dulvy et al., 2014). These species, found in a wide range of habitats all over the globe, are threatened by the destruction of critical habitat and the global expansion of shark and ray fishing driven by the demand for shark fins, meat, liver oil, and gill rakers. In addition, many shark and ray populations are vulnerable to increased mortality due to their slow growth rates, late sexual maturity, and low fecundity (Worm et al., 2013).

The Mozambique Channel, located between Mozambique and Madagascar, is a global hotspot for shark and ray species richness, endemism, and evolutionary distinctiveness with over 146 different species identified to date (Dulvy et al., 2014; Stein et al., 2018). However, there is also extensive fishing pressure throughout the region as more than 60% of the population is in some way dependent on marine resources for either sustenance or employment (Santos, 2008). Whether targeted or caught as bycatch, sharks and rays are heavily overexploited by artisanal fishers, semi-industrial, and industrial fleets in Mozambique. These fisheries operate over an extensive area using a variety of fishing gears, making monitoring and regulation difficult (WCS, 2021).

The Mozambique government recognizes the importance of conserving sharks and rays including the improved management of fisheries. The government is working with our client, Wildlife Conservation Society (WCS), to develop a National Plan of Action for shark and ray conservation, as well as an expanded network of marine protected areas with a goal of protecting 30% of the Mozambique exclusive economic zone (EEZ). While the MPA expansion planning process will identify priority areas for a broader set of marine resources, species, and habitats, our project focuses only on sharks and rays. Here, we lay out the framework of our spatial prioritization that identified key areas to protect based on shark and ray distribution, their critical habitats, and known fishing pressure. The results from our model will provide important information on priority areas for shark and ray conservation and can help inform how to incorporate these species into the on-going MPA planning process.

Results

The proposed networks of MPAs produced by our model identifies critical areas to protect for the most at risk sharks and rays in Mozambique based on their distribution and critical habitats. These recommended networks are based on scenarios that minimize impacts either on artisanal fishers, industrial fishers, and their combined fishing effort, or target areas with the highest fishing pressure.

As expected, the overall design of the MPA network changed significantly depending on the underlying objective of each scenario. When the objective was to minimize the impact on artisanal or industrial fisheries, the proposed network of protected areas shifted to offshore locations to avoid the artisanal and industrial fishing grounds close to shore. However, when the objective was to target areas of high fishing pressure, the proposed network of protected areas became more connected and shifted close to the shoreline. Each scenario ran through a suite of sensitivity analyses including varying spatial coverage as conservation targets from 10%, 20%, 30%, to 50%, design constraints, and using a boundary penalty to create larger and less-fragmented reserve networks.

The spatial prioritization model was built in R to be reproducible and is provided so our client can continue with future analysis and incorporate this work into their broader marine protected area planning process.

Conclusion

Designing and implementing MPAs is a complex planning process and must consider ecological, social and economic factors. By presenting a suite of recommendations and possible reserve designs, this model can help guide our client and the Mozambique government as they work to incorporate shark and ray conservation into their MPA planning process. Certain reserve designs in the different recommendations may be preferential depending on which stakeholders the government wants to prioritize or regulate. While these recommendations are helpful, our analysis had a number of limitations due to deficiencies in ecological data, stakeholder engagement, and information on a budget for implementation and enforcement. We recommend future research focus on incorporating updated ecological data as it becomes available, in particular aggregation sites and breeding grounds, as well as incorporating considerations for how these MPAs will be managed.

Objectives

The goal of this project is to help our client, Wildlife Conservation Society (WCS), and the government of Mozambique ensure the long-term persistence of sharks and rays through an expanded network of marine protected areas. The output of our analysis will augment the ongoing work of WCS and the government to create a National Plan of Action for the conservation and management of sharks and rays, and a broader strategic planning process to expand Mozambique's network of marine protected areas.

To achieve this goal, we have identified the following key objectives:

1. Identify priority areas to protect for the most at risk shark and ray species in Mozambique using a systematic spatial prioritization.
2. Provide recommendations of a network of marine protected areas for sharks and rays to WCS and the Mozambique government to incorporate into their larger marine protected area planning process.

Significance

Worldwide, marine biodiversity is under increasing threat from anthropogenic activities including fishing, habitat destruction, pollution, and climate change. Chondrichthyes (hereafter, “sharks and rays”), a class of marine cartilaginous fishes that includes sharks, rays, skates, and chimeras, are especially susceptible to anthropogenic threats due to their slow growth rates, late sexual maturity, and low reproductive capacity (Worm et al., 2013). Sharks and rays are found in a wide range of habitats globally, and are often upper trophic-level marine predators. They play critical roles in marine food webs and are vital to top-down regulation and maintenance of marine ecosystems (Cortez, 1999; Ebert & Bizzarro, 2007; Jacobsen & Bennett, 2013). The conservation of sharks and rays is essential to sustain coastal fisheries and marine ecosystems.

Unfortunately, one-quarter of sharks and rays are categorized as threatened according to the IUCN Red List (Dulvy et al., 2014). Extinction risk for many of these species is on the rise due to a global increase in shark and ray fishing, driven by rising demand for shark fins, meat, liver oil, and gill rakers. Declines in stocks of other fish species, as well as fishing restrictions, have led some fishers to alternatively target sharks and rays. Loss of critical habitat, such as coral reefs, is also elevating extinction risks for sharks and rays, as their breeding and nursery grounds are being damaged or slowly disappearing.

Over the past two decades, growing concern over population declines has led to multiple international deliberations and national commitments focused on conserving sharks and rays. Marine protected areas (MPAs) that specifically prohibit the fishing of sharks and rays are one approach increasingly being used to protect these species. However, efforts to design effective protected areas can be challenging due to a lack of quality data on species biology, life histories, population status, and fishery information such as undocumented illegal catches (Davis & Worm, 2014). As a result, effectively identifying target conservation areas requires careful consideration of each species' movements, biology, and critical habitats as well as socioeconomic and cultural factors (MacKeracher, T., et al, 2019). Still, marine protected areas can be effective for shark and ray conservation when MPA network designs and management are carefully planned. Key characteristics that have been identified as contributing to MPA success/failure include: level of community engagement, socioeconomic characteristics, ecological factors, MPA design, governance, and enforcement (Rossiter & Levine, 2014). Each of these factors are interconnected and require a complex plan that balances the needs of various stakeholders.

Our client, Wildlife Conservation Society (WCS), is currently working with the Mozambique government on a greater MPA prioritization project and a National Plan of Action (NPOA) for shark and ray conservation. Mozambique is a global hotspot for shark and ray species richness, endemism, and evolutionary distinctiveness (Dulvy et al., 2014; Stein et al., 2018). With a coastline spanning more than 2,770 km, Mozambique is home to millions of people dependent on marine resources. There is extensive fishing pressure on shark and ray species throughout the region from artisanal fisheries, coastal communities, and industrial fleets. Due to overexploitation, an estimated 37% of shark and ray species found in Mozambique are considered threatened with extinction (i.e. Vulnerable, Endangered, or Critically Endangered) according to the IUCN Red List (IUCN 2020). The Mozambique government recognizes the importance of conserving the abundance and diversity of sharks and rays in their national waters. However, Mozambique needs to implement policies and legislation dedicated to protecting these important species.

This project will contribute to the Mozambique government's development of conservation policies to better protect sharks and rays within their EEZ. Our analysis will augment the ongoing work of WCS and the government to create a National Plan of Action for the conservation and management of sharks and rays, and the broader strategic plan to expand Mozambique's network of marine protected areas. Our project aims to bring a scientifically rigorous method to determining optimal locations for MPAs specific to shark and ray conservation. Our spatial prioritization model is able to pinpoint optimal areas for MPA implementation by identifying vital conservation areas based on species distribution, critical habitat, and known aggregation sites, while also taking into account the needs of various stakeholders. Our reproducible spatial prioritization model will be incorporated into the greater MPA planning process being led by WCS. The outputs from our model will contribute to a larger effort of developing an international MPA network with Tanzania, Kenya, Madagascar and South Africa.

Background

Characteristics of Mozambique's Coastal Waters

Mozambique supports the highest diversity of sharks and rays in the Western Indian Ocean, with approximately 146 shark and ray species present within its exclusive economic zone (EEZ). Many of the shark and ray species that are classified as critically endangered depend on habitat located within the Mozambique Channel. These include southern Africa's most threatened endemic shark – the short-tail nurse shark (*Pseudoginglymostoma brevicaudatum*), as well as severely reduced populations of largetooth sawfish (*Pristis pristis*), green sawfish (*Pristis zijsron*), and bowmouth guitarfish (*Rhina ancylostomus*).

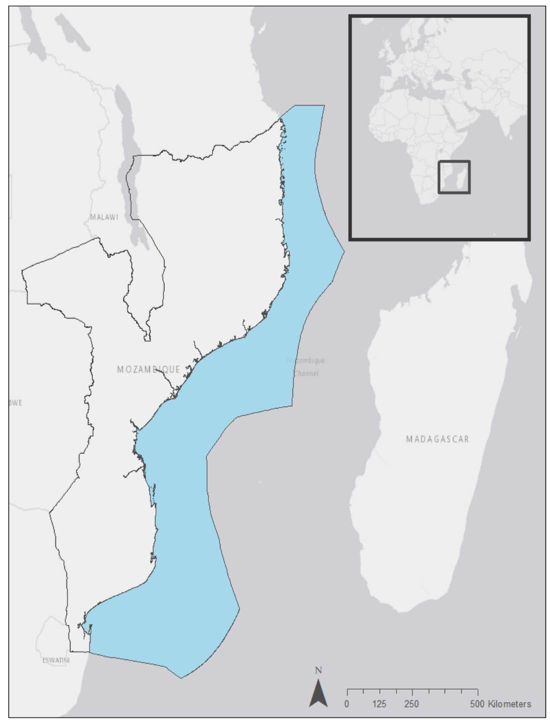

Figure 1. The project area, Mozambique exclusive economic zone, shown in blue.

Mozambique has the third-longest coastline in the region, spanning more than 2,770 km. Its EEZ encompasses an area approximately 562,000 km^2 in size with a continental shelf of approximately 104,300 km^2 (Ministry for the Coordination of Environmental Affairs, 2014). Within the EEZ there is a wide diversity of habitats that are crucial to sharks and rays, including coral reefs, seagrass beds, mangrove forests, and seamounts. Mozambique's dynamic channel is highly productive due to upwelling events, consistent climate variables, and ocean currents (Secretariat of the Convention on Biological Diversity, 2016). It has also been recognized as an Ecologically or Biologically Significant Marine Area by the Convention on Biodiversity (Secretariat of the Convention on Biological Diversity, 2016). Additionally, the Mozambique Channel has been identified as a shark hotspot of threat and priority based on three criteria: (1) the greatest number of threatened species, (2) greater than expected threats, and (3) high irreplaceability—high numbers of threatened endemic species (Dulvy et al, 2014). All of these characteristics make the Mozambique Channel a unique yet highly vulnerable area in need of effective conservation management.

Fisheries in Mozambique and Threats to Elasmobranchs

Approximately 60% of Mozambique's population, about 17 million people, live within the coastal zone (Pierce et al., 2008; Benkenstein, 2013). Improving and maintaining the sustainability of Mozambique's fisheries is of great importance as 3-4% of the national GDP comes from fisheries, and fish comprise about 50% of the population's protein intake (Doherty et al., 2015). Most people living along the coast are in some way dependent on marine resources, whether through commercial fishing, subsistence fishing, or employment in marine-related enterprises, such as fish processing, marketing, and ecotourism (Santos, 2008). Artisanal fisheries are especially important for Mozambique, accounting for more than 75% of landed marine fish. (Balanço Anual do Plano Económico e Social de 2018; Santos, 2008).

Management and regulation of artisanal fisheries is difficult in Mozambique due to the spatial dispersal, number of landing sites, lack of enforcement resources, diversity of species caught, and diversity of gear types used. Roughly 600 landing sites span the length of the coastline with most landings traded within the local economy (Benkenstein, 2013). Based on 2018 data, artisanal fisheries landings totaled 355,187 tons and were highest in the provinces of Zambézia, Nampula, and Sofala, with nearly 80,000 tons landed in Zambézia in 2018 (Balanço Anual do Plano Económico e Social de 2018).

At the industrial level, the major fisheries are tuna, shrimp, prawn, long-liners and general trawling (Balanço Anual do Plano Económico e Social de 2018). Each fishery uses different gear types and operates at various depths and locations. Industrial long-line fishing efforts are focused within the area of the Sofala Bank. The shrimp fisheries predominantly operate in the northern Sofala Bank area very near to shore, while prawn fisheries are mainly in southern Mozambique, nearshore. Industrial tuna fishing effort farther offshore, mainly in southern Mozambique. These differences in spatial location and gear type by fishery result in varied capture of sharks and rays in terms of species and quantity.

The Ministry of the Sea, Inland Waters and Fisheries (Ministério do Mar, Águas Interiores e Pescas) is the main government agency tasked with managing Mozambique's marine areas and fisheries. The Ministry faces difficulties in achieving complete or evenly distributed territorial coverage when it comes to issuing licenses, estimating total catch, and monitoring and enforcement (Balanço Anual do Plano Económico e Social de 2018). Management and monitoring of shark and ray harvests in Mozambique is particularly challenging. Shark fisheries have grown in recent years driven by a demand for fin exports, of which many presume are illegal (Pierce et al., 2008). Illegal, unreported, and undocumented fishing in Mozambique is estimated to be about 18% of the size of the legal fishery (Pierce et al., 2008).

Sharks and rays are caught in nearly all Mozambican fisheries, whether intentionally targeted or as a result of bycatch. According to the Ministry of Fisheries data, 4,313 tons of shark were harvested in 2018 and 77% came from the province of Zambézia (Balanço Anual do Plano Económico e Social de 2018). Based on landing data sampled across five coastal provinces from 2018-2020, the Sphyrnidae family accounted for 46% of the sharks and rays landed in Mozambique, with the scalloped hammerhead shark accounting for 31% of the total catch. Of the 1,090 elasmobranchs recorded, 55% of the individuals were threatened, falling into the IUCN Red List categories of Critically Endangered, Endangered, and Vulnerable. Based on the data collected, the capture of juveniles is of particular concern, as these sharks were removed before reproducing, thus not contributing to maintaining or growing the populations (WCS, 2021).

Current Conservation Policies

Laws and policies in Mozambique that regulate fisheries aim to promote sustainability and the long-term viability of marine resources (Rosendo, et al. 2011). Fishery regulations include licensing, gear restrictions, minimum size limits, seasonal closures for specific species, and prohibiting habitat destruction in coastal and marine ecosystems (Afonso, 2006). The success of these laws is reliant on the capacity of the government to enforce them, however, lack of resources contribute to less stringent enforcement of these policies (Rosendo, et al. 2011). In addition, enforcement varies for coastal versus off-shore fisheries, as well as between bordering countries such as South Africa, Tanzania, and Kenya (Chircop, et al, 2010). Motivation to enforce fisheries regulations can be tenuous given how heavily many people in Mozambique rely on the fisheries for their livelihoods.

In the past decade, Mozambique has committed to various global policy frameworks and conservation tactics defined by the CBD's Aichi Targets and the Conservation of Migratory Species of Wild Animals (CMS). These include the implementation of MPAs and protection of specifically annexed shark and ray species under the IUCN and CITES criteria (Convention on Biological Diversity, 2004). Specifically, Mozambique is a signatory to the Aichi Targets, committing to converting 30% of its coastal and marine areas into MPAs by 2020. Approximately 572,000 km^2 of the country is considered coastal and marine area (about 42% of the country), which would mean an area of 171,600 km^2 would need to be protected in order to achieve this goal (Ministry for the Coordination of Environmental Affairs, 2014). There are currently five designated marine protected areas in Mozambique that make up around 30,155 km^2.

As of January 2021, Mozambique revised their fisheries laws Regulamento da Pesca Marítima (REPMAR) with new policies that increase protection for sharks and rays and promote sustainable fisheries. These laws clarify how Comunitários de Pesca (CCPs), the principal bodies managing local fisheries, can become legally recognized entities. Once recognized, CCPs can designate community-managed fishing areas allowing local fishers to decide what gear types can be used, carve out no-take zones, or impose temporary closures (Vyawahare 2020). Empowering local communities to make vital decisions about their livelihoods has the potential to increase compliance and sustainable fishing practices.

Additionally, the revised REPMAR contains new laws specific to shark and ray conservation. Any sharks caught as bycatch must be released and any landed sharks must not be mutilated or de-finned. Other new regulations ban destructive fishing practices on critical habitats such as mangroves, seagrasses, and reefs. Lastly, the updated law enacts full protection for several threatened species including whale sharks, manta rays, and mobula species (Vyawahare 2021).

Mozambique Marine Protected Area Network and Conservation Efforts

To date, 30,155 km^2 of Mozambique's EEZ is designated as marine protected areas. Each MPA has different levels of regulation and management, with the various designations including national parks, reserves, total protection zones, sanctuaries and environmental protection areas. MPA placement has been determined based on the best available scientific data, political-economic drivers, and an evaluation of social conditions in the target areas (Rosendo, et al. 2011). MPAs in Mozambique are largely utilized to achieve conservation targets and support the growth of tourism (Motta, 2008).

Sharks and rays can benefit from MPAs, however, it is important to consider these species' unique characteristics in a MPA network design process. Some of the major ecological principles that should be considered for effective designs include – protection of representative habitats; replication of habitats; protection of areas critical to specific life stages; focus on areas where habitats and populations of focal species are in good conditions with low threats; networks that allow movement between MPAs; large areas and/or a focus on connectivity (Rigby, et al. 2019). MPAs that are well-designed for sharks and rays and combine other fisheries management measures to reduce mortality will be most effective. Some general features of effective shark and ray MPAs include separation from fished areas by habitat boundaries, long-term protection, and inclusion of habitat that is of high value to the target species (Rigby, et al. 2019).

WCS is working with the Mozambique Government to greatly expand the current MPA network, with a goal of 30% coverage of the EEZ by 2030. Determining optimal placement of the new MPAs is a complex task that must consider ecological, social, and economic factors to maximize conservation benefits while considering local dynamics and institutional constraints (Rosendo, et al. 2011). This project aims to identify priority areas to protect the most at risk shark and ray species for incorporation into the greater MPA planning process. By focusing our spatial prioritization specifically on protection of sharks and rays, we can help ensure that these important species and their unique characteristics will be adequately accounted for in the final MPA network design for Mozambique.

Data & Methods

General Approach

To achieve our objective to provide recommendations of a network of marine protected areas for sharks and rays to WCS and the Mozambique government, we decided to use a spatial prioritization to identify key areas within Mozambique's EEZ to protect for the most at risk shark and ray species. When designing a network of MPAs for specific species, ecological factors, such as habitat and species range, are important characteristics to consider. However, long-term success of MPAs also depends on a number of other factors including level of community engagement, socioeconomic characteristics, network design, governance, and enforcement (Rossiter & Levine, 2014). The more these various factors are considered in the planning process, the more likely the MPA network will be successful long-term. This includes considering how these factors overlap or might impact different stakeholders. For example, a reef area that is a critical habitat for sharks may also be an important fishing ground for local subsistence fishers. By closing the reef off to fishing via an MPA, the sharks may be better protected but the fishers' livelihoods may be severely impacted. In order to determine optimal reserve design for sharks and rays, given these tradeoffs, we conducted a systematic spatial prioritization. This prioritization process determines optimal locations of protected areas that meet conservation objectives while minimizing costs to different stakeholders. By running different scenarios within the spatial prioritization model we show how by focusing on different factors of MPA success leads to different reserve designs. The output of our analysis will augment the broader strategic planning process to expand Mozambique's network of marine protected areas. The model itself is fully reproducible and can be added to, adjusted, and re-run to be further incorporated into the larger marine protected area planning process.

Ecological Data

The available data used as the foundation of our spatial prioritization was ecological data on critical habitat, species' ranges, aggregation sites, as well as fishing pressure data on artisanal and industrial fishing effort.

Focal Species

Our analysis focused on 16 shark and 11 ray species that have been proposed for listing on Mozambique Protected Species List and are considered the most at risk of extinction. Our client, WCS, and a group of experts identified this list of species as the most in need of improved management based on their conservation status and whether these species are endemic or have restricted ranges within Mozambique. These species are either classified as critically endangered (CR) or endangered (EN) according to IUCN Red List classification, listed by the UN Convention on the Conservation of Migratory Species of Wild Animals (CMS), listed by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) as appendix I, or protected by the Indian Ocean Tuna Commission (IOTC).

To assess ecological characteristics of each species including their range, movement, preferred depth, critical habitat, and aggregation sites, we used the online global biodiversity information system FishBase, IUCN range maps, knowledge from local shark biologists on our client team, and a literature review of published studies. We found that 19 out of 27 focal species are considered migratory, and of these, 12 species have ranges that span the entire Mozambique EEZ according to IUCN. Given that so many focal species are highly mobile and migratory, we identified known aggregations sites and critical habitats where species congregate for feeding, breeding and nursery grounds. This allowed our model to prioritize these critical life-stage areas where species reproduce, mature and forage. Many of these migratory pelagic shark and ray species are often found near coastal waters surrounding the continental shelf. Each species appears at different depths but all utilize the nutrient-rich ecosystem encompassing the shelf. Some characteristic species found along the shelf are dusky sharks (*Carcharhinus obscurus*), great hammerheads (*Sphyrna mokarran*), shortfin mako shark (*Isurus oxyrinchus*), oceanic whitetip (*Carcharhinus longimanus*), and several skate species (Bonfil et al., 2008; Compango et al. 2005; Compango et al., 2007; Compango et al. 1989; Stevens, 2009). According to FishBase a number of the migratory sharks are also typically found at very shallow depths between 0-30 meters including ragged-tooth shark (*Carcharias taurus*), scalloped hammerhead (*Sphyrna lewini*), smooth hammerhead (*Sphyrna zygaena*), and zebra shark (*Stegostoma fasciatum*). See Table 1 in the Appendix for a complete list of focal species and their movement, depth, and critical habitats.

Species Distribution

We downloaded IUCN range maps for each focal species and reviewed these with shark biologists familiar with the region. The shark biologists determined how accurate these were at a local scale and helped us to refine range maps for three of the species based on their local knowledge. These included short-tail nurse shark (*Pseudoginglymostoma brevicaudatum*), bottlenose wedgefish (*Rhynchobatus australiae*), and whitespotted wedgefish (*Rhynchobatus djiddensis*).

In addition, our client provided us with baited remote underwater video data or BRUV data and landing statistics. This data captures species occurrences from 3 locations in the Mozambique Channel over the past 18 months and while this is important data to collect, we were not able to bring it into our model because it wasn’t robust enough for our analysis and would have skewed our results. However, we used this data in our analysis in other ways, such as validating our habitat and species distribution maps around these 3 areas for the species identified in the dataset.

Critical Habitat

We also included identified critical habitats, areas that contain habitat features essential to the conservation of a species, that our focal species depend on for a variety of reasons such as cleaning stations, nursery habitats, and foraging grounds. Even pelagic sharks, who often migrate long distances and generally spend most of their time in the open ocean do occasionally occur close to shore, making them vulnerable to coastal fisheries. The five critical habitats we identified as important include: reefs, mangroves, seagrass, seamounts & knolls.

Reefs

Reef habitats serve as critical habitat for many elasmobranch species. For example, many rays aggregate at reefs in Southern Mozambique for periodic cleanings by reef fishes. Some frequent visitors include the shortfin devil rays (*Mobula kuhlii*) and giant manta rays (*Mobula birostris*) (Murie, C. & Marshall, A., 2016). Giant manta rays also utilize reef ecosystems as foraging grounds (Boggio-Pasqua et al., 2019; Marshall, 2008). In addition, these reef habitats are used for socializing and mating (Boggio-Pasqua et al., 2019). Some species like short-tail nurse sharks (*Pseudoginglymostoma brevicaudatum*) are permanent residents at coral reefs throughout their life (Osgood, G. & Baum, J., 2015). Whale sharks (*Rhincodon typus*) are also known to aggregate in local, highly productive near-shore areas such as coral reefs (Stevens, 2007; Duffy, 2002). Rocky reefs are also a key critical habitat for many elasmobranchs such as the zebra shark (*Stegostoma fasciatum*) who seasonally aggregate at rocky-reefs and rest on the sandy bottom nearby (Compagno, 2002; Dudgeon et al., 2013). Juvenile ragged-tooth sharks (*Carcharias taurus*) are more commonly caught in rocky reefs, inferring that they spend large parts of their lives in this type of habitat. Adult ragged-tooth sharks typically dominate areas such as the surf zone, shallow bays, and deeper areas around the outer continental shelves (Dicken et al., 2006; Compagno et al., 2005).

Mangroves

The second critical habitat we identified was mangroves which provide habitat and nursery areas for several elasmobranch species, including juvenile scalloped hammerhead sharks (*Sphyrna Lewini*), one of the most threatened of our focal species (Zanella et al. 2019). Sawfish (*Pristis spp.*) also rely on mangroves throughout their life cycle (Moore, 2014; Duly et al., 2016).

Seagrass

Seagrass plays a critical role in the marine food web and can be indicators of a healthy ecosystem and areas with minimal human degradation (Sievers, M. et al., 2019). Seagrasses are susceptible to human perturbations such as pollution, runoff, and physical disturbance. Seagrass beds are used by reef sharks and ray species for nursery and foraging grounds, demonstrating habitat use patterns (Chin, A. et al., 2012). The great hammerhead shark (*Sphyrna mokarran*) also tends to inhabit coastal areas, and typically prefers tidal flats and seagrass flats (Compagno et al., 2005; Roemer at el., 2016). Sawfish utilize seagrass habitats in their later life cycles. As juveniles, sawfish tend to stay in estuaries and rivers, but once grown the adult sawfish can remain in the estuaries or migrate to mangrove and seagrass habitats (Poulakis et al., 2013).

Seamount & Knolls

Similar to reefs, seamounts serve as an aggregation site for many of our focal species. For example, the pelagic thresher shark (*Alopias pelagicus*) and scalloped hammerhead (*Sphyrna lewini*), two typically oceanic species, aggregate close to shore at seamounts for foraging and cleaning (Klimley & Butler, 1988; Oliver et al., 2011). Additionally, the giant manta ray (*Mobula birostris*) has been known to frequent seamounts (Marshall, 2008).

Aggregation Sites

We also consulted with local shark biologists and reviewed published studies to identify and manually create a spatial layer in ArcGIS of aggregation sites in the Mozambique Channel. We found sites for four of the species on our list: gray reef shark (*Carcharihinus amlyhnycos*), reef manta ray (*Manta alfredi*), giant manta ray (*Mobula birostris*), and whale shark (*Rhincodon typus*). Manta rays and whale sharks tend to aggregate periodically or seasonally to forage. Manta rays also aggregate to use reefs as 'cleaning stations' or at inshore areas to mate. Multiple studies conducted near popular dive sites off Praia de Tofo (23.85° S, 35.54° E) in the Inhambane Province observed aggregations of manta rays using coral reefs in the study area as cleaning stations. Over the same study period researchers observed a whale shark aggregation in coastal waters within 8 km south of Praia do Tofo (Marshall et al., 2011; Rohner et al., 2013). This same area is a known mating and birthing ground for reef manta ray (*Manta alfredi*), with individuals typically giving birth December - February (Marshall & Bennett, 2010). A large aggregation of over one hundred gray reef sharks (*Carcharihinus amlyhnycos*) has been observed near Vimize Island in the northern part of the Quirimbas Archipelago (Hill et al., 2009).

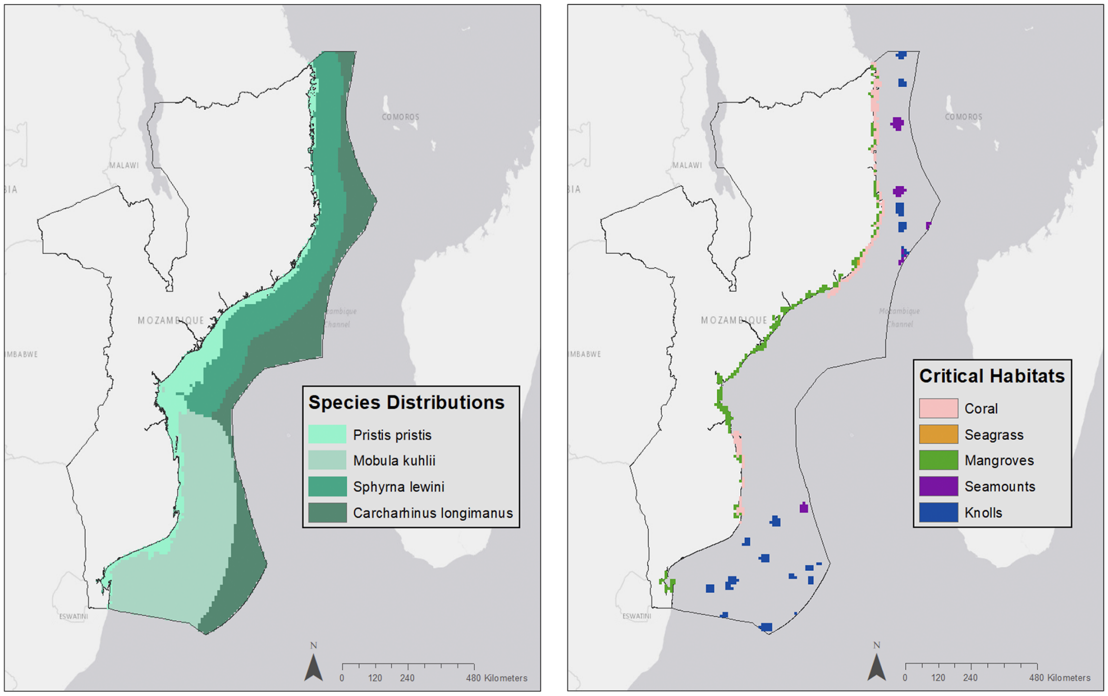

Figure 2. Conservation features: (a) species distribution for four of the focal species including Pristis pristis, Mobula kuhlii, Sypherma lewini, and Carcharhinus longimanus, and (b) five critical habitats including coral, seagrass, mangroves, seamounts, and knolls.

Fishing Pressure Data

As mentioned above, socioeconomic characteristics are an important factor to consider in MPA network design. Although detailed socioeconomic data is limited, we included fishing pressure data as a way to address the effects MPAs will have on fishers and the resulting socioeconomic implications. The Mozambique government has expressed their intention to minimize the impact of MPAs on fishers, and therefore, avoid conflict resulting from MPAs placed in areas with high fishing pressure. By putting MPAs in areas with low fishing pressure, MPAs are less likely to displace fishers from their most productive fishing grounds and therefore, avoid negative impacts on fisher livelihoods and profits.

We obtained data related to both artisanal and industrial fishing efforts in Mozambique. Artisanal fishing effort was based off of district level fishing effort data from 2017, measured in fishing days, provided to us by the Ministry of Fisheries. Industrial fishing was mapped using vessel monitoring systems (VMS) data provided by the Mozambique government as a proxy for industrial fishing effort. The VMS data was point data from vessels across four industrial fisheries: long-line, shrimp, gamba, and tuna. Design and use of this fishing pressure data is explained in more detail in the description of the model. Given there may be greater interest in regulating industrial fishers and minimizing impact of MPAs on artisanal fishers, or vice versa, we ran scenarios in our model that looked at artisanal and industrial fishing pressure separately and as a combined fishing pressure layer.

By incorporating ecological and fishing pressure data into the model we address the ecological factors and socioeconomic characteristics that are important for successful MPA network design. The model also incorporates parameters that address MPA success factors such as fragmentation, governance, and enforcement.

Technical Approach

The systematic conservation planning tool prioritizr R package was used to determine the optimal reserve designs within the Mozambique exclusive economic zone (EEZ). Prioritizr uses integer linear programming (ILP) to determine optimal locations of protected areas that meet conservation objectives while minimizing costs. It is similar to Marxan, another conservation planning tool, however instead of using simulated annealing to solve the optimization problem, the ILP algorithm finds the exact optimal solution (Hanson et al., 2020). To create this model, we had to first define the following parameters: problem objective, planning unit, conservation features, cost of implementation, boundary penalty, features to lock-in or out, time-limit, and number of model runs.

Problem Objective

In prioritizr, the problem objective defines the overall goal of the conservation plan. This can be done a number of ways including using a minimum set objective which minimizes the cost of a reserve network, while ensuring all targets are met; maximum features objective, which fulfills as many targets as possible within a specific budget; maximum phylogenetic diversity objective which maximize phylogenetic diversity of features within a specific budget; and more. Our analysis used this first type, minimum set objective function, which minimizes the cost of our design while meeting conservation targets that we specify. Given capacity and resource limitations in Mozambique, we determined that minimizing cost was critical to success of a MPA network in Mozambique since it would give us an efficient solution to meet our conservation targets. With no monetary-related data available, proxies of cost to stakeholders were used instead of specific dollar amounts.

The chosen minimum set objective function can be expressed mathematically as:

$$\textit{Minimize} \sum_{i=1}^{I} \mathbf{x}_i \mathbf{c}_i \quad \textit{subject to} \quad \sum \mathbf{x}_i \mathbf{r}_{ij} \geq \mathbf{T}_j \textit{ for all } \boldsymbol{j} \textit{ there exists } \boldsymbol{J}$$

I indexed by **i** is the planning units, **J** indexed by **j** is the set of features, $\mathbf{x}_i$ is the decision variable that specifies whether a planning unit is selected or not, $\mathbf{c}_i$ is cost of the planning unit, $\mathbf{r_{ij}}$ is the amount of feature j in planning unit **i**, and $\mathbf{T_j}$ is the target for feature **j** (Hanson et al., 2020).

Planning Unit

Once we identified our problem objective, the next processing step was to divide the project area, the Mozambique EEZ, into a set of planning units at a scale that was appropriate for the ecological features included in the analysis. Studies have shown that the size of the planning unit can impact the outcomes of the reserve design, so it was important to carefully consider the spatial scale of the planning unit (Shriner et al, 2006). A shapefile of the Mozambique EEZ was provided by our client, WCS, and was rasterized in R to produce a grid of cells at a 10km^2 resolution.

Conservation Features

We included spatial data of species distribution and five critical habitats important for sharks and rays as conservation features in the model. As discussed in the data section above, our analysis focused on 16 shark and 11 ray species that WCS and a group of experts identified as the most in need of improved management. Each of the 27 species' IUCN range maps was used as a conservation feature in our model. In addition, we included spatial data on five types of critical habitats that are important for elasmobranchs including reef, mangroves, seagrass, seamounts & knolls. For the reef habitat conservation feature we used a polygon spatial layer of Global Benthic Habitats created by Allen Coral Atlas using Planet Dove 3.7 m resolution daily satellite imagery, wave models, and ecological data. The polygon shapefile was rasterized and clipped to the project area. For mangroves, we used a dataset of the global distribution of mangroves that was created by the UNEP World Conservation Monitoring Centre using earth observation satellite imagery. For seagrass, we used a global distribution of seagrass compiled by the UN Environment World Conservation Monitoring Centre along with many other organizations and project contributors. Similar to the previous habitat files, we created a raster from the polygon shapefile and clipped it to the project area. Lastly, we used a global distribution of seamounts and knolls created by Yesson et al. that was based on 30-second bathymetry data. We created a raster from the point data and clipped it to only include data within the project area.

Cost of Implementation

Different spatially explicit measures of cost were explored to represent the cost of lost fishing opportunity. This is similar to a method used by Ban et al. that specifically examined using socioeconomic data in data-poor regions (2009). In spatial plans, costs data are represented in different ways. For example, costs can represent the physical cost of purchasing land or the opportunity cost of foregone commercial activities. For our analysis the costs used include: (1) area; (2) artisanal fishing pressure; (3) industrial fishing pressure, (4) combined fishing pressure, and (5) the inverse of combined fishing pressure.

Area

To explore an optimal conservation design that does not consider costs to specific stakeholders we used planning unit area as a surrogate for cost. Since our planning units are uniform in size, we set the cost to be uniform across our entire project area. This uniform cost will not give us useful solutions that minimize a cost to any stakeholder, however, we can use this as a baseline scenario to compare our other outputs to as we add more complex costs.

Artisanal Fishing Pressure

To explore the impacts that marine protected areas have on artisanal fishers, we created an artisanal fishing pressure layer. We considered creating this layer using a gravity model similar to Cinner et al. that uses population density and mean travel time to estimate fishing pressure. However, based on conversations with the Mozambique government, population density does not correspond with fishing pressure. For example, the capital of Mozambique, Maputo is the largest population center in the country but does not have heavy artisanal fishing pressure.

To create this proxy, we instead used district level fishing effort from 2017, measured in fishing days, and country-wide mean distance traveled by fishers to assign a fishing pressure value to each cell within the travel range. We set points at 1 km intervals along the entire coastline and for each district, divided the total effort by the number of coastal points within that district, so that each point along the coast had a fishing effort assigned to it. Next, we used the Kernel Density tool within ArcGIS with these inputs to create a search radius to distribute this fishing effort from each coastal point. Based on information provided by the Mozambique government, the average maximum distance traveled by artisanal fishers is 15 km. For each 1 km ocean cell in the output, the kernel density function searched within a 15 km radius and summed the values of any coastal district points. As such, the further an ocean cell was from shore, the less points were likely to be included, which is why the fishing effort values decrease further offshore. After 15 km to any shoreline, the fishing effort is zero.

In addition to assigning a fishing pressure value to each cell, we cut the artisanal fishing layer to certain depths. Based on conversations with the Mozambique government we know that artisanal fishers rarely fish past 50 meters depth in most regions of the country. There are a few districts in central Mozambique where the bathymetry is shallower because of the presence of the Sofala Bank. In these areas, artisanal fishers rarely fish past 30 meters depth. Those depths were used as the outer range of the artisanal fishing layer with ocean cells beyond the 30/50m bathymetry cutoff set to a fishing pressure of 0. Additionally, we log transformed the artisanal fishing layer and rescaled it between 0 and 1 to place it on a unitless scale that allows direct comparison across cost layers.

Industrial Fishing Pressure

To minimize the impacts and conflicts that marine protected areas have on industrial fishers, we created an industrial fishing pressure layer. This layer was created using VMS data provided by the Mozambique government as a proxy for industrial fishing effort. The VMS data was point data from vessels across four industrial fisheries - long-line, shrimp, gamba, and tuna. The point data was smoothed into a kernel density raster for each fishing gear. Since the VMS data is not comprehensive, the kernel density surface was used to interpolate values where there are no fishing points within a search radius. In this way, areas with lots of fishing points receive high values, areas with fewer points receive low values, and areas beyond a 20 km search radius receive values of 0. We log transformed each of the industrial fishing layers and rescaled them between 0 and 1 to put them on a unitless scale that allows direct comparison across cost layers. We then combined them into one cumulative industrial fishing pressure layer and rescaled the cumulative layer between 0 and 1.

Combined Fishing Pressure

To minimize the impacts and conflicts that marine protected areas have on all fishers in Mozambique's EEZ, artisanal and industrial, we created a combined fishing pressure layer. The Mozambique government has expressed their intention to minimize the impact of MPAs on fishers, presumably both artisanal and industrial, and therefore avoid conflict resulting from MPAs placed in areas with high fishing pressure. Since the aim of this layer is to prioritize outputs that avoid overlap with high fishing pressure areas, artisanal and industrial fishers were weighted equally. We combined the artisanal and industrial fishing pressure layers and rescaled the cumulative layer between 0 and 1.

In order to maximize the protection of sharks and rays from areas of high fishing pressure we also created an inverse of this combined fishing pressure cost layer. For this, we used the inverse of the combined fishing cost layer so that our model prioritized protection of areas with the highest fishing pressure and rescaled it between 0 and 1, where 0 was areas with the lowest fishing pressure and 1 was areas with the highest fishing pressure.

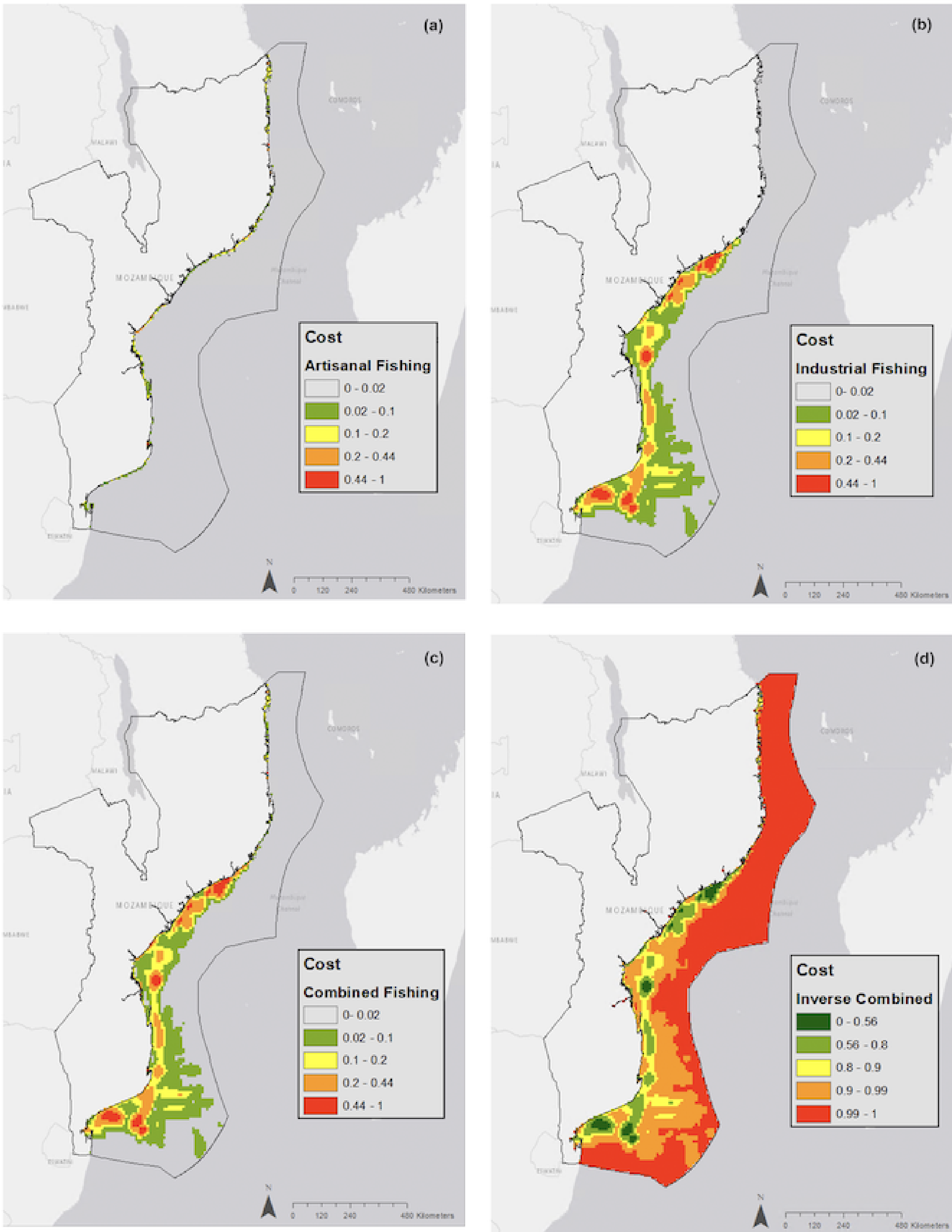

Figure 3. Maps of the different cost layers used in the analysis: (a) artisanal fishing cost, (b) industrial fishing pressure, (c) combined fishing pressure, and (d) inverse of combined fishing pressure.

Conservation Targets

The targets are the minimum amount of our conservation features' distribution that needs to be protected and included in the prioritization (or reserve design). These targets can be thought of as a quantitative interpretation of our conservation goal, and thus should be set at the amount required to ensure the long-term persistence of our focal species. Ideally, targets should be based on scientific knowledge of each of our species and critical habitats (SANBI & UNEP-WCMC, 2016). However, in the absence of more detailed scientific knowledge, we used a range of target scenarios set at 10%, 20%, 30%, and 50% to explore how these varying targets impact the overall layouts and percentage covered of the EEZ. For example, if we set a conservation target of 20%, the reserve system must include at least 20% of each species distribution and at least 20% of each critical habitat in the output.

Boundary Penalty

We also used the boundary penalty (which is similar to the boundary length modifier in Marxan) that can be used to penalize solutions that are excessively fragmented. Since many of the focal species are considered migratory, we wanted to avoid highly fragmented solutions in our analysis. However, we also want to avoid excessively large reserves that are unrealistic to implement and manage. To do this, Prioritizr uses a numeric penalty that scales the importance of selecting planning units that are clumped together or connected. Using a boundary penalty is a trade-off, i.e. by setting a high boundary penalty the model will prioritize solutions that are less fragmented, yet more expensive. This is counter to the overall goal of minimizing cost. For this reason, a boundary penalty can have a large influence on the output, so it is important to carefully consider the appropriate boundary penalty to use.

There are a few different methods to determine an efficient boundary penalty. We used a common method adapted from Stewart and Possingham (2005) by running a series of 11 different boundary penalty values starting with 0, then exponentially increasing from $1x10^{-8}$ to 1. We then plotted the results of these eleven runs, comparing the cumulative boundary length (total perimeter) of the reserve design of the output against the average area of the output (see Figure 10 in the Appendix). This produced an optimization curve, which demonstrated a drop off of the curve at the boundary penalty of 1×10^{-6}, after which the curve appeared unstable. To further home in on this value range, we ran the same analysis with the slightly larger boundary penalties of 2×10^{-6}, 3×10^{-6}, 5×10^{-6}, 7×10^{-6}. The boundary penalty of 1×10^{-6} still appeared to be the optimal point on the curve, optimizing the relationship between boundary length and average area. This boundary penalty is what we used throughout the analysis as it provided a good tradeoff between clustering of reserve design and cost.

Locked-In Constraints

Marine Protected Areas & Key Biodiversity Areas

Another consideration in the model was any additional features we wanted to lock-in and/or lock-out from the solution specific planning units. We decided to lock in existing marine protected areas, since these areas are already designated as protected by the government, to always be included in the outputs. We also ran some model runs that locked in the known aggregation sites, and other model runs that locked in key biodiversity areas, sites that contribute significantly to the global persistence of biodiversity according to criteria set by the IUCN. We chose these features to test in our reserve design because of the enforcement, management and ecosystem implications they may have on a larger reserve network. For example, areas with existing MPAs may not need more protection (lock-out MPAs), or alternatively, expansion of existing MPAs (lock-in MPAs) may provide ecological and management benefits.

Aggregation Sites

We decided to include aggregations sites as a locked-in constraint on some model runs to see if these impacted the reserve design. We had limited aggregation site data (3 sites total) so we decided to only include these sites in some scenarios and include this as a future improvement on the analysis once more aggregation site data is available.

Time Limit & Gap

Another consideration was the length of time to run each model scenario. Each run could take over 48 hours given the number of planning units and the limited computer processing we had available to determine an optimal solution with a gap of zero (the gap refers to the numeric gap to optimality). Given our time constraints, we set a time limit of 6 hours to run the optimizer for each scenario, at which point the solver returns the current best solution. This resulted in an optimality gap ranging from 0-30%, depending on the boundary penalty value we used.

Model Runs

As mentioned above, determining optimal placement of MPAs is a complex task that must consider ecological, social, and economic factors in order to maximize both conservation benefits and probability of success. Ecological factors are important to weight in order to provide optimal protection to sharks and rays. However, the effects of MPAs on stakeholders must also be considered and weighed against potential ecological benefits. By running different scenarios within the spatial prioritization model we show how focusing on different factors leads to different results in terms of reserve design. By presenting a range of models results, we will provide our client and the Mozambique government with options to guide their decision-making process.

We explored varied conservation priorities through different model runs, described below. Each scenario seeks to prioritize a certain group of stakeholders or ecological result. Prior to running these scenarios, we ran several simulations to find an efficient boundary penalty value and to test the sensitivity of our targets and planning unit constraints. We set a time limit of 6-hours for each model run.

Scenario 1: Baseline

The objective of this scenario was to protect important areas for sharks and rays based on the probability of their distribution and location of suitable habitats using a uniform cost for all planning units. For this run, we used area as the cost, set targets of 20% for all conservation features, locked in planning units that included existing MPAs, and set a boundary penalty to zero. This scenario provides a baseline from which to compare scenarios that consider costs to stakeholders.

Scenario 2: Minimal Impact on Artisanal Fishing

The objective of this scenario was to protect important areas for sharks and rays in a way that minimizes impact on artisanal fishers. Avoiding MPA placement in areas of high artisanal fishing pressure assumes artisanal fishers' most productive fishing grounds will remain open. This scenario is optimal if the government wants to place MPAs in areas of low artisanal fishing pressure to avoid conflict with artisanal fishers and minimally disrupt their livelihoods. For this run, we used artisanal fishing pressure as the cost, set targets of 20% for all conservation features, locked in planning units that included existing MPAs, and set a boundary penalty to zero.

Scenario 3: Minimal Impact on Industrial Fishing

The objective of this scenario was to protect important areas for sharks and rays in a way that minimizes the impact on industrial fishing fleets. Avoiding MPA placement in areas of high industrial fishing pressure assumes industrial fishers' most productive fishing grounds will remain open. This scenario is optimal if the government wants to place MPAs in areas of low industrial fishing pressure to avoid conflict with industrial fishers. For this run, we used industrial fishing pressure as the cost, set targets of 20% for all conservation features, locked in planning units that included existing MPAs, and set a boundary penalty to zero.

Scenario 4: Minimal Impact on All Fisheries

The objective of this scenario was to protect important areas for sharks and rays in a way that minimizes the impact on both artisanal and commercial fishers. Avoiding MPA placement in areas of high fishing pressure assumes fishers' most productive fishing grounds will remain open. This scenario is optimal if the government wants to place MPAs in areas of low fishing pressure to avoid conflict with all fishers. For this run, we used a combined fishing pressure layer that incorporates the artisanal and industrial fishing pressure layers as the cost, set targets of 20% for all conservation features, locked in planning units that included existing MPAs, and set a boundary penalty to zero.

Scenario 5: Target Areas with High Fishing Pressure

The objective of this scenario is to maximize the protection of sharks and rays. Given that fishing, both direct targeting and bycatch, is the greatest threat to sharks and rays in Mozambique, this scenario would be ideal for conserving sharks and rays as it would place MPAs in areas with the highest fishing pressure. For this, we used the inverse of our combined fishing cost layer from scenario 4, so that our model prioritized protection of areas with the highest fishing pressure.

Results

Through our five scenario model runs we show how prioritization of different factors leads to different MPA network design. As our client and the government work to determine optimal placement of MPAs, results from some scenarios may be preferential, depending upon which stakeholders the government wants to prioritize or regulate. Given that this analysis is highly reproducible and we will be passing the model to WCS for further use, the results shown here are not limited, final options. Rather, these results demonstrate different solutions for priority areas depending on the criteria selected. The model can easily be rerun by our client in the future to account for new data or changing priorities.

Running models with the five different cost layers of area, artisanal fishing pressure, industrial fishing pressure, combined fishing pressure, and inverse of combined fishing pressure yielded different solutions for priority areas. Before running each scenario, various sensitivity analyses were performed to determine the appropriate parameters, including locking-in and locking-out existing MPAs, Key Biodiversity Areas, and aggregation sites, various boundary penalties, and conservation targets (10, 20, 30, and 50%). Based on the results of the sensitivity analyses, the five different scenarios were run using a conservation target of 20%, no boundary penalty and the efficient boundary penalty (1 x 10^{-6}), and locking-in existing MPAs (all sensitivity analysis runs can be found in the Appendix).

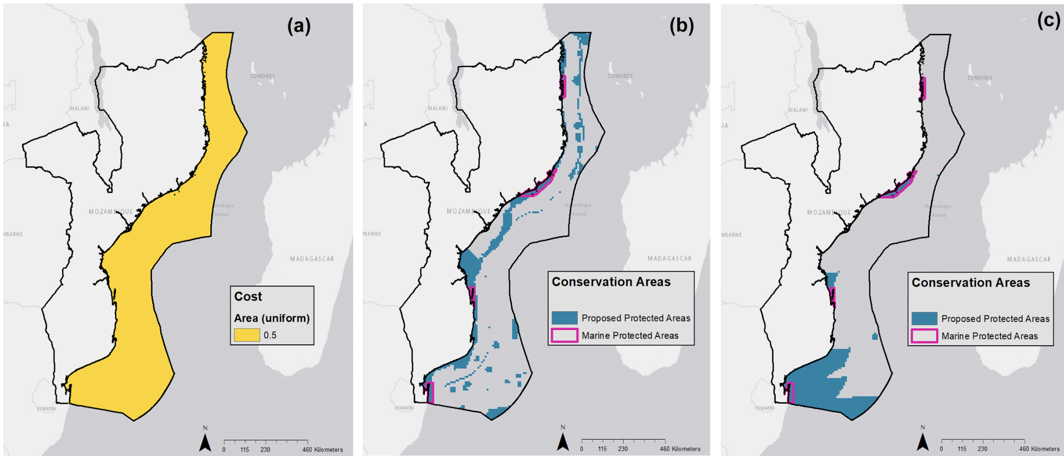

Figure 4. Prioritizr results for Scenario 1 using a uniform cost across the project area shown in (a) to compare different boundary penalties of (b) 0 and (c) $1x10^{-6}$ with conservation targets of 20%, and existing marine protected areas locked-in.

Figure 4 shows the baseline scenario or suggested protected area without considering effects on stakeholders. The cost layer (Figure 4a) shows the uniform cost of 0.5 across the entire EEZ. The inputs for the two prioritization models for the baseline scenario are uniform targets of 20% for all conservation features and locked in existing marine protected areas (Figure 4b & c). The boundary penalty was set to zero (Figure 4b) and the efficient boundary penalty (Figure 4c) to compare different levels of fragmentation. Since there is a uniform cost in the scenario, the recommended priority areas closely mirror the conservation features. This scenario provides a baseline from which to compare scenarios that consider costs to stakeholders.

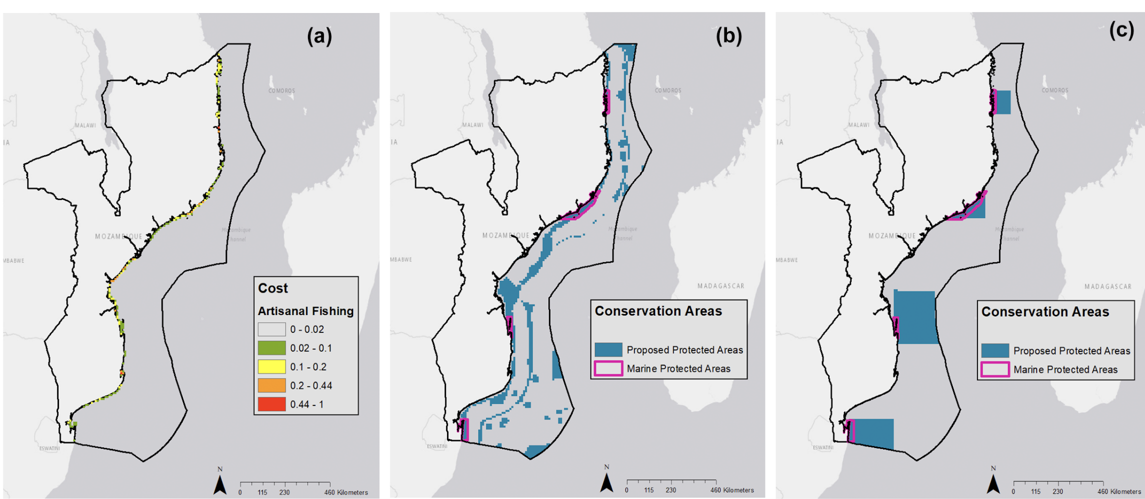

Figure 5. Prioritizr results for Scenario 2 - Minimal Impact on Artisanal Fishers: using artisanal fishing pressure as cost (a) to compare different boundary penalties of (b) 0 and (c) $1x10^{-6}$ with conservation targets of 20%, and existing marine protected areas locked-in.

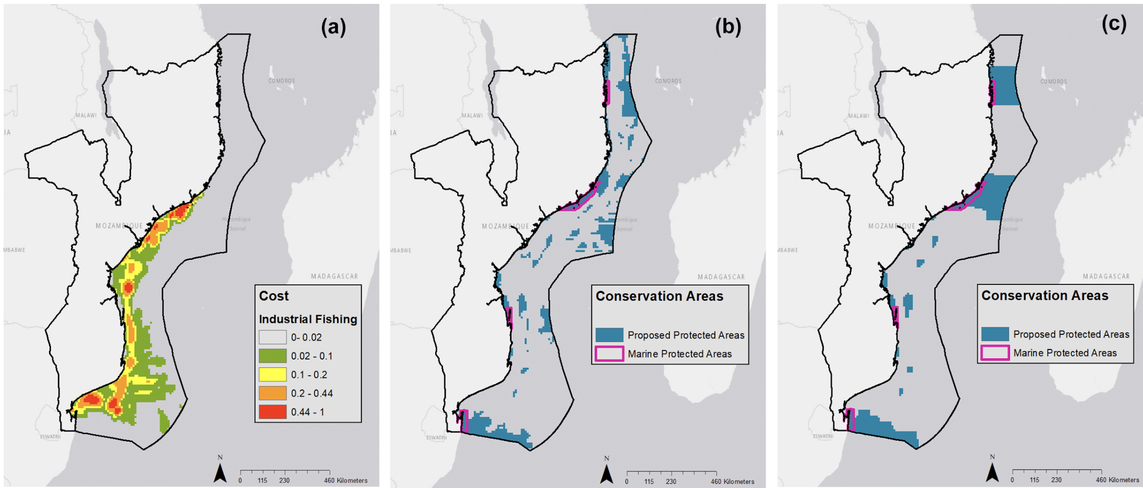

Figure 6. Prioritizr results for Scenario 3 - Minimal Impact on Industrial Fishers: using industrial fishing pressure as cost (a) to compare different boundary panelites of (b) 0 and (c) $1x10^{-6}$ with conservation targets of 20%, and existing marine protected areas locked-in.

Overall design of the marine reserve network varies depending on which cost layers are used in the model run. For scenarios 2 and 3, the model prioritized areas that minimized cost to artisanal and industrial fishers, respectively, while also protecting 20% of the critical habitats and species distribution. Scenario 2 sought to place MPAs in areas with low artisanal fishing pressure, to decrease displacement of artisanal fishers from their most productive fishing grounds. The results of this prioritization were farther offshore (Figure 6b & c), which is to be expected since the highest artisanal fishing pressure occurs close to shore within 0-30 meters of depth.

Scenario 3 sought to place MPAs in areas with low industrial fishing pressure, to decrease displacement of industrial fishers from their most productive fishing grounds. Hotspots of industrial fishing pressure are found farther offshore than artisanal fishing pressure, and are mostly concentrated in the southern part of the EEZ. Therefore, the suggested protected areas for this scenario focus more in the north and along a strip of the southern border where industrial fishing tends not to occur (Figure 7b & c).

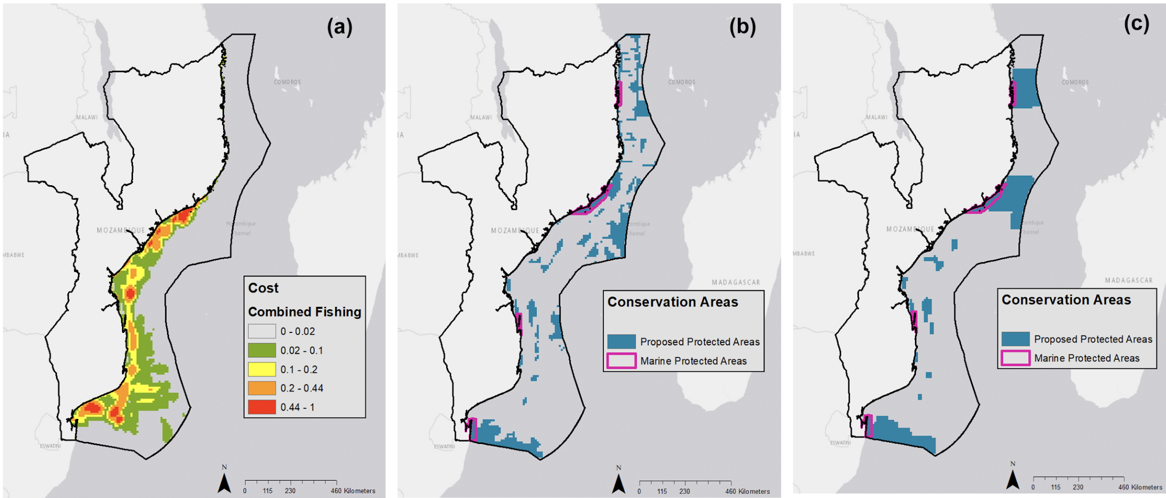

Figure 7. Prioritizr results for Scenario 4 - Minimal Impact on all Fisheries: using combined fishing pressure as cost (a) to compare different boundary penalties of (b) 0 and (c) $1x10^{-6}$ with conservation targets of 20%, and existing marine protected areas locked-in.

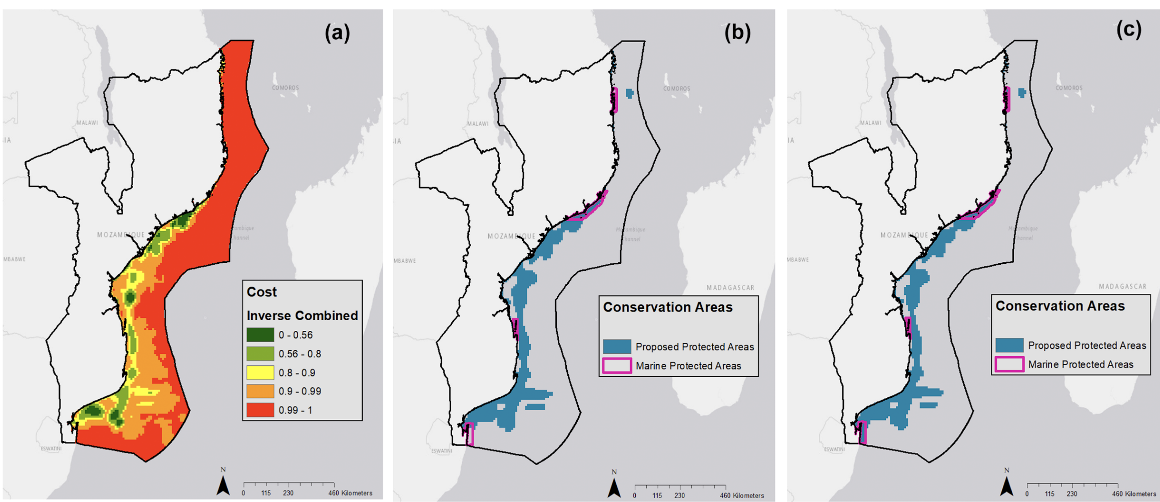

Figure 8. Prioritizr results for Scenario 5 - Target Areas with High Fishing Pressure: using the inverse of combined fishing pressure as cost (a) to compare different boundary penalties of (b) 0 and (c) $1x10^{-6}$ with conservation targets of 20%, and existing marine protected areas locked-in.

Scenario 4 prioritized areas with low fishing pressure in order to minimize cost to all fishers, while also protecting 20% of the critical habitats and species distribution. The results of this prioritization suggested three general areas (Figure 7b & c) to protect, in the south, north and central-east regions of the EEZ. When using an efficient boundary penalty (Figure 7c) the areas are more clumped and contiguous when compared with no boundary penalty (Figure 7b).

Scenario 5 used the inverse cost layer of scenario 4, with differing areas prioritized as a result. This scenario sought to offer the greatest protection to sharks and rays by placing MPAs in areas with higher fishing pressure. The results (Figure 8b & c) form a continuous area parallel to and generally not far from the shoreline. This is to be expected as these areas in the central and south region just offshore have the highest fishing pressure.

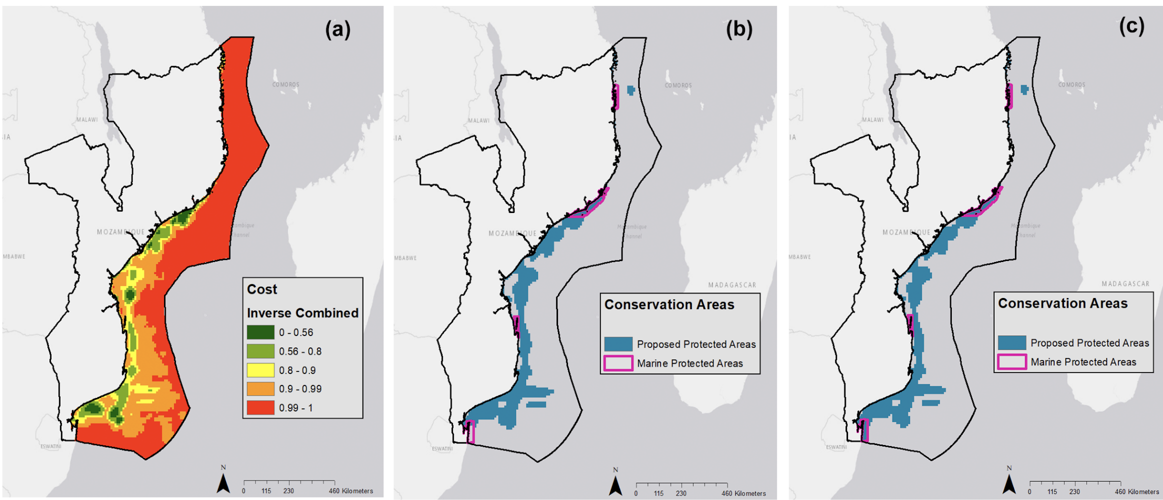

Figure 9. Prioritizr results for management scenario using distance decay from 40 meter depth and beyond as cost (a) to compare different boundary penalties of (b) 0 and (c) 1×10^{-6} with conservation targets of 5%, and existing marine protected areas locked-in.

In addition to the five scenarios described above, we also ran the model to prioritize areas closer to shore, by using a distance decay from 40m depth and beyond as a cost (Figure 9). This is to factor management of the MPAs into the analysis. Management of MPAs by CCPs and artisanal fishers will require that the MPAs are within the depth range that artisanal fishers typically travel (0-30/50m depth). If MPAs are managed by government officials, MPAs closer to shore will be less costly to manage as they will require less time and fuel to reach for patrols. The results of this model run are therefore nearshore.

Discussion

Implications of the Results

Our objective is to provide recommendations on MPA network design for sharks and rays to the Mozambique government based on the results of our systematic marine spatial prioritization. By presenting all five of our scenarios, we will be providing our client and the Mozambique government with options to guide their decision-making process. Determining optimal placement of MPAs is a complex task that must consider ecological, social, and economic factors in order to maximize both conservation benefits and probability of success. We explored different conservation priorities through the five scenarios to show how prioritizing different factors leads to different MPA reserve designs. Different reserve design results may be preferential, depending upon which stakeholders the government wants to prioritize or regulate.

The first scenario provides a baseline of where priority areas should be implemented based on shark and ray biology and ecology, without considering effects on stakeholders. This scenario is ideal for shark and ray conservation, since it conserves 20% of critical habitat and species distribution, but does not account for stakeholder priorities. The result of scenario 1 can be used to compare the results from the scenarios that incorporate costs. The second and third scenarios incorporate effects on stakeholders, and prioritize minimizing conflict with fishers while still achieving 20% conservation targets. We analyzed artisanal fishers (scenario 2) and industrial fishers (scenario 3) separately to see how the reserve design changes based on where each fishing pressure is located within the EEZ. By presenting the results of each of these scenarios, the government will have the option to focus on specific stakeholders. For example, if the government wanted to minimize the impact of the MPA network on artisanal fishers, but was willing to place MPAs in productive industrial fishing grounds they might be most interested in the results of scenario 2. Scenario 4 combines artisanal and industrial fishing pressures, weighting them equally, and these results will be helpful if the government prioritizes avoiding conflict with both fisheries.

Because fishing pressure is one of the greatest threats to sharks and rays in Mozambique, our last model (scenario 5) specifically targets areas of high fishing pressure. Since both the artisanal and industrial fisheries are contributing to the decline of shark and ray populations, due to overfishing and bycatch, this scenario would be ideal for conserving sharks and rays. However, implementing protected areas in the most productive fishing grounds could negatively affect fishers' livelihoods and may be difficult to enforce and manage.

In addition to changing the cost layers for each scenario, we also conducted sensitivity analyses on several key parameters. Increasing the conservation targets from 20% to 50%, for example, greatly increased the percentage of the EEZ that would need to be protected (shifting from 19% coverage of the EEZ to 49%). If budget and enforcement were not considered, we would recommend reserve designs that meet the high target scenario of 50%, since these designs would ensure a larger portion of species distribution and critical habitats are protected. However, we have concluded that 20% may be a more reasonable target for conservation features and that 50% changes the reserve design beyond a reasonable area to protect given the limited capacity of enforcement in Mozambique. Another parameter we manipulated was locking-in MPAs. We found that including existing MPAs could be useful since it did not change the overall layout too drastically and would make implementation easier as the expanded area could be incorporated into existing management plans and increase connectivity.

Overall, we found that some of the parameters we manipulated had significant impacts on reserve design. While some areas were prioritized every time, regardless of the scenario we ran, the overall network design changed significantly depending on the cost layers used and if a boundary penalty was included. In order to address this, we mapped the results of all five scenarios together to determine areas that were consistently prioritized regardless of the parameters used (Figure 16). Based on this, the following areas are recommended to be added to the current MPA network: offshore areas with seamounts and knolls in the northern third of Mozambique's EEZ; areas along the shoreline in the northern third of Mozambique's EEZ where critical coral habitat is located; the outer edge of the Sofala Bank; nearshore areas north of Bazaruto Archipelago National Park with critical coral and mangrove habitat; offshore areas with knolls along the southern edge of Mozambique's EEZ. As the government and stakeholders negotiate tradeoffs of MPA placement in different areas, these "hotspots" that are prioritized across most scenarios may be easier to compromise on for implementation.

Assumptions and Limitations

Our objective was to prioritize areas that optimally protect the most at-risk shark and ray species in Mozambique. Our analysis only considered 26 focal species and their critical habitats and ranges. While all of these species were included because of their conservation status, not all of them are targeted for the meat and fin trade. Therefore, our results encompass a group of species that all have differing reasons for their threatened status. This is a limitation in our ability to recommend highly specific networks with management plans that address the specific reason these species are so vulnerable.

We also considered the migratory and wide-ranging nature of some of our species and the effect this might have on the reserve design. Our data relied on IUCN species distribution maps and an extensive literature review on the species' critical habitats. By including the critical habitats we aimed to capture any species ranges that were not included in the IUCN datasets, as well as potential aggregation sites and critical life-stage habitats. Even with this type of data, many of the species in our analysis were data deficient and therefore, accuracy and resolution of our outputs are limited. As research and understanding of these species' movements evolve, we recommend including data on the nuances of their individual behaviors and geographic distribution patterns. This could include data on differences between male and female geographic ranges, and more specific areas of occurrences (AOO) and the extents of occurrences (EOO) data as available. A more detailed analysis of species' home ranges could be important in considering the size and shape of MPAs for sharks and rays. Overall, more abundant and finer resolution data will improve the accuracy and usefulness of this analysis and should be incorporated into the reproducible model as it becomes available.

In order to address the mobile and migratory nature of the species in our analysis, we included a boundary penalty to account for the fragmentation of our reserve design. Limiting the fragmentation of the reserve design is important as MPAs are more successful from an ecological and management perspective when they are less fragmented. Additionally, because most of the species in our study are mobile, the reserve design had to be somewhat contiguous to protect these species at all of their life stages. This is the biggest challenge and limitation in using MPAs for mobile species, but by including key aggregation sites and nursery grounds in our analysis, we hope that our reserve designs will at least protect these species at their most vulnerable life stages.

Overall, the connectivity of our recommendations will be considered by local experts and the Mozambique government. WCS is conducting a similar and more robust spatial prioritization, analyzing MPA reserve design generally. It is likely that pieces of this analysis will be incorporated into the holistic marine spatial planning analysis. Issues of fragmentation and overall reserve connectivity may be better addressed at a later stage of the process, as the final MPA network will be focused on protecting all aspects of the marine environment, not just sharks and rays. Connectivity will also be assessed in consideration with bordering nations to make a more connected reserve network along the coast of southeastern Africa.

Considerations for Future Analysis

In addition to the limitations noted above, other important considerations were beyond the scope of our project and are recommended for future analysis. One such consideration is redistribution of fishing effort in response to MPA implementation. When a fishing area is closed, the fishing that took place there will either cease to exist, and fishing effort overall will decline, or the fishing effort will move elsewhere (Cabral et al., 2017). Given the importance of artisanal fisheries on livelihoods in Mozambique it is highly unlikely that fishing effort would diminish as a result of MPAs. Redistribution of effort is a more likely outcome, which can concentrate effort elsewhere, in the areas bordering MPAs or in unprotected regions (Jaiteh et al., 2016). This concentration of effort can then have its own impacts on the marine environment, potentially leading to negative conditions around MPAs. Such socioeconomic responses to MPA placement are difficult to predict. However, fishing responses should be considered in MPA design and ideally monitoring post-implementation can help to better understand the impacts of fishing effort dynamics on overall marine health.

Research on the spillover effect caused by MPAs is another consideration that could be included in a more complex model. Limited research has been done on MPA spillover effect of sharks and rays specifically. Research on this topic would require detailed data on home ranges and spatial patterns of specific shark and ray species. Alternatively, MPAs providing spillover effects for other species is well documented; this could provide an indirect benefit to sharks and rays if their food sources increase in abundance as a result of MPAs. Generally, shark species with highly resident behavior benefit more from MPAs, while sharks with a larger home range require larger MPAs for protection (Dwyer et al., 2020). Because of this, future analyses might put less weight on migratory species, and more priority on resident species where site-based management is more effective.

Another consideration for future analysis is accounting for range shifts of shark and ray species due to climate change. Planning ahead for species redistributions has been shown to have minimal tradeoffs and can greatly decrease exposure to risks from climate change (Pinsky et al., 2020; García Molinos et al., 2016). Proactively planning for range shifts southward over time should be considered not only in future analyses for shark and ray MPAs, but as part of the entire MPA planning process for Mozambique.

Considerations for Implementation

The analysis and results of this report will be incorporated into the greater MPA prioritization and implementation project that WCS is working on in conjunction with the Mozambique government. The final design of the MPA network in Mozambique will likely incorporate aspects of this project, to ensure protection of sharks and rays within the network. However, the final recommendations of network design will need to consider other factors related to practical implementation that were beyond the scope of this analysis. To that end, it is important to consider how this analysis should be used and elaborated upon to ensure MPA network design is practical and successful from the perspective of community engagement, socioeconomic characteristics, governance, and enforcement (Rossiter & Levine, 2014).

The first major consideration is which, if any, fisheries to target in the implementation of MPAs. Scenarios 2 and 3 show the results of the network design when trying to avoid the highest effort fishing areas for artisanal and industrial fishers, respectively. Conversations with WCS have implied that the government may be looking to avoid conflict with fishers and place MPAs in areas with low fishing pressure. Artisanal fishers account for 80-90% of all catch in Mozambique, so are likely having the largest impact on sharks and rays (UNCTAD, 2017). According to official government landing statistics, shark landings are higher in the artisanal fisheries, with 1,900 tons of shark landed by artisanal fishers in 2017, compared with 319 tons landed in 2013 by the industrial fleet (Balanço Anual do Plano Económico e Social de 2018). However, the amount of sharks caught in the semi-industrial and industrial fisheries is relatively unknown and research done on tuna longliners in the western Indian Ocean has shown large numbers of sharks and rays being caught as bycatch (Pierce et al., 2008; Gheng et al., 2018). Due to the lack of data and prevalence of IUU catch in Mozambique, it is difficult to say with certainty which fishery, artisanal or industrial, is more negatively affecting shark and ray populations.

From an economic and livelihood perspective, about 20% of the entire population of Mozambique depends on fishing for part of their income, and 50% of the total animal protein consumed nationally comes from fisheries (UNCTAD, 2017). Placing MPAs in artisanal fishers' optimal fishing grounds could therefore be quite detrimental to the livelihoods of large portions of the population. The vast majority of the industrial fleet is foreign vessels, predominantly from Portugal, Spain, and China, and much of their catch is not landed in Mozambique (UNCTAD, 2017). While the industrial fleet accounts for only 7% of total catch, the catch accounts for 57% of total monetary catch value across all fisheries (UNCTAD, 2017). Regulating the industrial fleet via MPAs would have less of an impact on the livelihoods of people in Mozambique but could lead to lost profits for the government. These tradeoffs, for both the artisanal and industrial fisheries, should be considered when deciding whether to target MPAs towards or away from specific fishing grounds.

Regardless of which fisheries are affected, engaging stakeholders in the MPA planning process will be critical to its success. A review conducted in 2011 noted that establishment of MPAs in Mozambique has followed a top-down approach with limited community involvement and that many communities have felt left out of the process and are suspicious of the ultimate goals of the MPAs (Benkenstein, 2013). While our project tried to take into consideration the impact of MPAs on fishers, we were lacking direct stakeholder input and engagement. Stakeholders can play a significant role in the implementation of any conservation plan, especially when livelihoods of large populations are at stake as is the case with marine protected areas in Mozambique. More direct engagement with different stakeholders such as industrial fishers, co-managed fisheries groups, and government officials would strengthen this analysis. Qualitative research in Mozambique found that some of the main perceptions of MPAs amongst artisanal fishers were - concerns over closing fishing grounds, desire to be involved in the decision making process, concerns over lack of enforcement, negative effects on livelihoods, feelings that industrial fishers are more heavily impacting the fisheries yet regulation and enforcement of MPAs are directed toward artisanal fishers (Rosendo et al., 2011). WCS will be conducting a stakeholder survey in the coming months which will provide further insight into the human dimensions of MPA implementation. This survey will be an important first step in beginning to build fisher buy-in to the process of MPA development and management.

Currently, there is variability in the types of enforcement and management of MPAs in Mozambique. They range from co-managed community fisheries that manage no-take and partial take reserves, to TURF reserves in the north where fishers manage and fish their own area of the ocean, to government enforced no-take marine protected areas. Some of these are recognized by the government and regulated, while others are not well enforced. Because of the dynamic nature of management and enforcement it was not feasible to systematically incorporate type of enforcement and the associated costs or budget into our analysis. However, based on general budget constraints and the nature of the fisheries in

Mozambique it would seem that MPAs managed and enforced by local fishers is the most appropriate and feasible form of management as the MPA network expands.

Comunitários de Pesca (CCPs) are community fisheries councils charged with local management of fisheries. Hundreds of CCPs are scattered along the 2,700 km coastline. Their size, organizational and institutional capacity, and level of governance vary greatly and they often lack support and training to carry out their work effectively (Benkenstein, 2013; Samoilys et al., 2017). However, fisheries laws (REPMAR) updated in January 2021 clarify how CCPs can become legally recognized entities, which provides a path forward for community co-management of fisheries and future MPAs (Vyawahare, 2021). Beginning to engage CCPs in the planning process will be critical to the success of the MPA network. The long shoreline of Mozambique as well as limited government capacity makes effective marine governance and enforcement extremely challenging. As of 2011, there were only two government vessels allocated to patrol the entire Mozambique exclusive economic zone (Benkenstein, 2013). As a result, it will be necessary for the government to work with the co-managed fisheries along the coast to manage the new network of proposed MPAs.

If MPAs within the network are to be predominantly managed by CCPs, certain considerations should be taken in terms of network design. As of 2013, only 41% of artisanal fishers in Mozambique use boats, and of those that use boats, less than 10% are motorized (UNCTAD, 2017). Additionally, based on information provided to WCS by the government, artisanal fishers rarely fish past 50 m depth, or 30 m depth in the Sofala Bank region. These statistics indicate that placing MPAs offshore and delegating management to artisanal fishers will be unfeasible, as they will not be able to easily access the MPAs in order to patrol and enforce. To address these management considerations we conducted a model run to prioritize areas within a 0-40m depth range (Figure 9). These results may be more practical from a management perspective; if artisanal fishers (CCPs) are in charge of management they will more easily be able to access and patrol MPAs closer to shore. Alternatively, if MPAs are managed by government officials, MPAs nearer to shore will require less fuel to access and therefore be less costly to manage. However, achieving Mozambique’s goal of 30% of their EEZ protected via MPAs will be very difficult to achieve if large offshore areas are not included in the network design. Additionally, case studies have shown that very large MPAs that border many fishing communities are more difficult to manage. Distribution of fishing rights and coordination amongst many communities raises challenges compared with one or two communities managing a single reserve. Size and location of MPAs must therefore be considered in final network design based on proposed management type.

As mentioned previously, WCS is conducting a similar and more robust spatial prioritization, analyzing MPA reserve design generally. Mozambique is aiming to protect 30% of its EEZ in MPAs by 2030. It is likely that pieces of this analysis will be incorporated into the holistic marine spatial planning analysis. However, results of the shark and ray prioritization are unlikely to be considered for all 30% of the network design. Given this, we analyzed the spatial coverage resulting from our different model runs (Table 2) to guide decision makers when considering shark and ray prioritization within the greater planning process. Additionally, issues of fragmentation and overall reserve connectivity may be better addressed at a later stage of the process, as the final MPA network will be focused on protecting all aspects of the marine environment, not just sharks and rays. With this reproducible model, we have created a foundational analysis for spatial shark and ray conservation from which to build off of. The spatial prioritization model will be passed to our client who will be able to update and adapt it as new data becomes available and priorities shift.

Finally, while an MPA network that specifically considers sharks and rays is an important step in conserving these species, MPAs need to be paired with other conservation efforts to ensure full protection. Sharks and rays are mobile species that must be protected when moving between MPAs. For this reason, continued improvement of existing fishing regulations, education and awareness campaigns, and participation in legal conventions and treaties focused on shark and ray protection, are all complementary strategies that the government must employ in addition to the MPA network. WCS's continued work on the development of the National Plan of Action for shark and ray conservation is critical to ensuring that sharks and rays are protected in Mozambique through various channels beyond MPAs.

Conclusion

Well-designed marine protected areas can provide substantial benefits and play a key role in conserving sharks and rays around the globe. However, to be successful, they will require buy-in from local communities, as well as resources to carefully plan, manage, and enforce. A spatial planning model can help resource managers and governments like Mozambique, that have limited resources, design networks of protected areas that protect sharks and rays while considering the impacts on fishers and their livelihoods. The results of the spatial prioritization described in this report can be used by WCS and the Mozambique government to ensure that design of the overall MPA network incorporates areas of importance for sharks and rays. Future research on species' reproductive biology, ecology, and movement is imperative alongside other conservation efforts and as it becomes available, this data can be incorporated into our reproducible spatial model. The species in our analysis are migratory, have low fecundity, and are highly targeted. These realities are complex and will require more than a MPA network alone for long-term protection, however, building a well-designed MPA network is an important starting point and could provide benefits to these endemic and irreplaceable species in the long term.

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Appendix

Tables

Table 1. Focal shark and ray species used in the project which included the top 16 shark and 11 ray species experts recommend for listing on Mozambique Protected Species List based on their conservation status, limited range, and demand by fisherman. The information on species movement came from shark biologists at Wildlife Conservation Society, the preferred depths are from Fishabse, and the habitats were from a literature review. Note the species with asterisks (**) indicate species that had inaccurate data, so range maps were created based on local knowledge and expertise.

SHARKS				
Species	**Common Name**	**Migratory (WCS)**	**Depth (FishBase)**	**Habitats (LitReview)**
Alopias pelagicus	pelagic thresher shark	Migratory f	usually 0 - 150 m	seamounts
Alopias superciliosus	bigeye thresher shark	Migratory f	usually 1 - 100 m	
Alopias vulpinus	common thresher shark	Migratory f	usually 0 - 200 m	
Carcharihinus amlyhnycos	gray reef shark		usually 0 - 280 m	
Carcharhinus longimanus	oceanic whitetip	Migratory f	usually 0 - 152 m	outer continental shelf
Carcharhinus obscurus	dusky shark	Migratory f	usually 200 - 400 m	outer continental shelf
*Pseudoginglymostoma brevicaudatum***	short tail nurse shark	Endemic (WIO)	unknown	coral reefs
Carcharodon carcharias	great white shark	Migratory f	usually 0 - 250 m	reefs; continental shelf; coastal bays
Isurus oxyrinchus	shortfin mako shark	Migratory f	usually 100 - 150 m	continental shelf
Isurus paucus	longfin mako shark	Migratory f	unknown	
Carcharias taurus	ragged-tooth shark	Migratory f	usually 15 - 25 m	coral reefs; outer continental shelf
Rhincodon typus	whale shark	Migratory f	usually 0 - 100 m	
Sphyrna lewini	scalloped	Migratory f	usually 0 - 25 m	seamounts,

	hammerhead			shallow coastal areas
Sphyrna mokarran	great hammerhead	Migratory f	usually 1 - 100 m	deep coral reefs, continental shelves, seagrass
Sphyrna zygaena	smooth hammerhead	Migratory f	usually 0 - 20 m	
Stegostoma fasciatum	zebra shark		usually 5 - 30 m	

RAYS				
Species	**Common Name**	**Migratory (WCS)**	**Depth (FishBase)**	**Habitats (LitReview)**
Mobula alfredi	reef manta ray	Migratory f	usually 1 - 120 m	
Mobula birostris	giant manta ray	Migratory f	usually 1 - 120 m	coral reefs, seamounts
Mobula kuhlii	shortfin devil ray	Migratory f	unknown	coral reefs
Mobula mobular	giant devil ray	Migratory f	unknown	
Pristis pristis	largetooth sawfish	Migratory f	usually 25 - ?	estuaries; mangroves; seagrass
Pristis zijsron	green sawfish		usually 5 - 70 m	estuaries; mangroves; seagrass
Rostroraja alba	spearnose skate		usually 50 - 500 m	continental shelf; shallow bays
Rhina ancylostomus	bowmouth guitarfish		usually 3 - 90m	coral reefs; sand flats; estuaries
*Rhynchobatus australiae***	bottlenose wedgefish		usually 0 - 60 m	continental shelf
*Rhynchobatus djiddensis***	whitespotted wedgefish	Migratory f	usually 1 - 75 m	
Acroteriobatus leucospilus	greyspot guitarfish		usually 1 - 100 m	

Table 2. Percent of Mozambique EEZ covered by MPAs under each scenario.

Scenario	*Target*	*Boundary Penalty*	*EEZ Coverage (%)*
Scenario 1 - Baseline	*10%*	*0*	*10.05 %*
Scenario 1 - Baseline	*20%*	*0*	*20.01 %*
Scenario 1 - Baseline	*30%*	*0*	*29.99 %*
Scenario 1 - Baseline	*50%*	*0*	*49.93 %*
Scenario 1 - Baseline	*10%*	*0.000001*	*10.05 %*
Scenario 1 - Baseline	*20%*	*0.000001*	*20.05 %*
Scenario 1 - Baseline	*30%*	*0.000001*	*30.02 %*
Scenario 1 - Baseline	*50%*	*0.000001*	*49.93 %*
Scenario 2 - Artisanal	*10%*	*0*	*10.05 %*
Scenario 2 - Artisanal	*20%*	*0*	*20.01 %*
Scenario 2 - Artisanal	*30%*	*0*	*30.02 %*
Scenario 2 - Artisanal	*50%*	*0*	*50.00 %*
Scenario 2 - Artisanal	*10%*	*0.000001*	*10.05 %*
Scenario 2 - Artisanal	*20%*	*0.000001*	*20.01 %*
Scenario 2 - Artisanal	*30%*	*0.000001*	*30.04 %*
Scenario 2 - Artisanal	*50%*	*0.000001*	*56.94 %*
Scenario 3 - Industrial	*10%*	*0*	*10.05 %*
Scenario 3 - Industrial	*20%*	*0*	*20.01 %*
Scenario 3 - Industrial	*30%*	*0*	*29.99 %*
Scenario 3 - Industrial	*50%*	*0*	*49.93 %*
Scenario 3 - Industrial	*10%*	*0.000001*	*10.05 %*
Scenario 3 - Industrial	*20%*	*0.000001*	*20.03 %*
Scenario 3 - Industrial	*30%*	*0.000001*	*30.01 %*
Scenario 3 - Industrial	*50%*	*0.000001*	*56.62 %*

Scenario 4 - Combined	*10%*	*0*	*10.05 %*
Scenario 4 - Combined	*20%*	*0*	*20.02 %*
Scenario 4 - Combined	*30%*	*0*	*30.06 %*
Scenario 4 - Combined	*50%*	*0*	*50.05 %*
Scenario 4 - Combined	*10%*	*0.000001*	*10.05 %*
Scenario 4 - Combined	*20%*	*0.000001*	*20.01 %*
Scenario 4 - Combined	*30%*	*0.000001*	*30.01 %*
Scenario 4 - Combined	*50%*	*0.000001*	*56.16 %*
Scenario 5 - Inverse	*10%*	*0*	*10.05 %*
Scenario 5 - Inverse	*20%*	*0*	*20.00 %*
Scenario 5 - Inverse	*30%*	*0*	*29.99 %*
Scenario 5 - Inverse	*50%*	*0*	*49.93 %*
Scenario 5 - Inverse	*10%*	*0.000001*	*10.05 %*
Scenario 5 - Inverse	*20%*	*0.000001*	*20.01 %*
Scenario 5 - Inverse	*30%*	*0.000001*	*29.99 %*
Scenario 5 - Inverse	*50%*	*0.000001*	*49.93%*

Figures

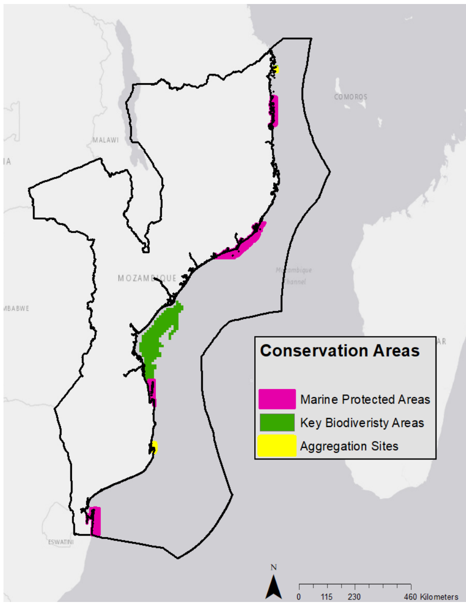

Figure 10. Location of existing marine protected areas, key biodiversity areas, and the known-aggregation sites.

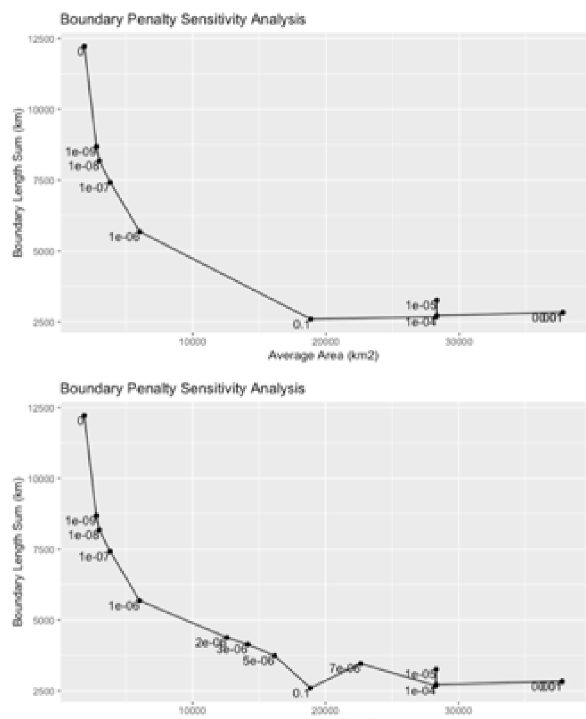

Figure 11. Boundary Penalty Sensitivity Analysis: the trade-off between total reserve system boundary length (km) and the average area of the reserve system (km^2) for boundary penalties between 0 and 1.

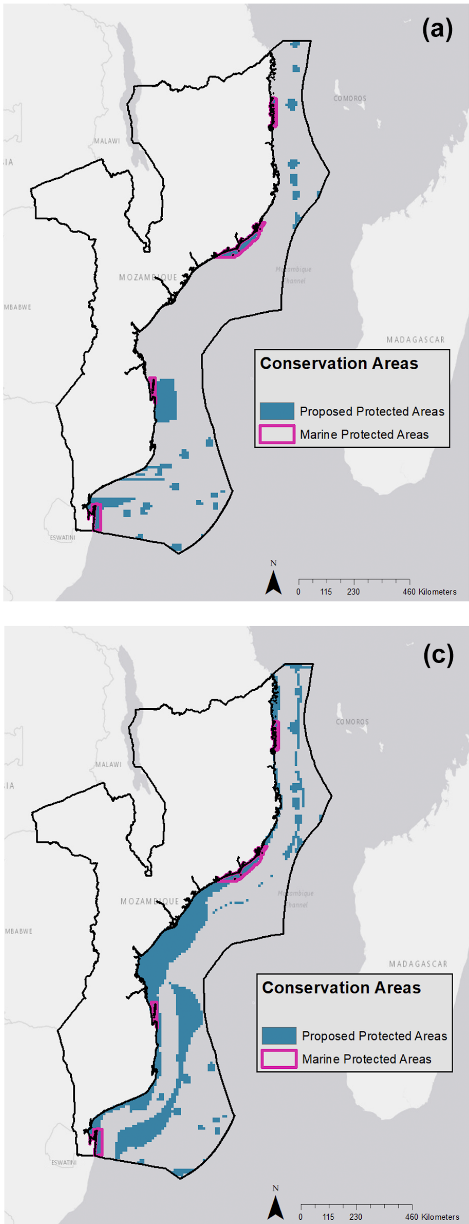

Figure 12. Prioritizr results comparing different targets set at (a) 10% (b) 20%, (c) 30%, and (d) 50% using area as cost (baseline scenario), no boundary penalty, and including existing marine protected areas.

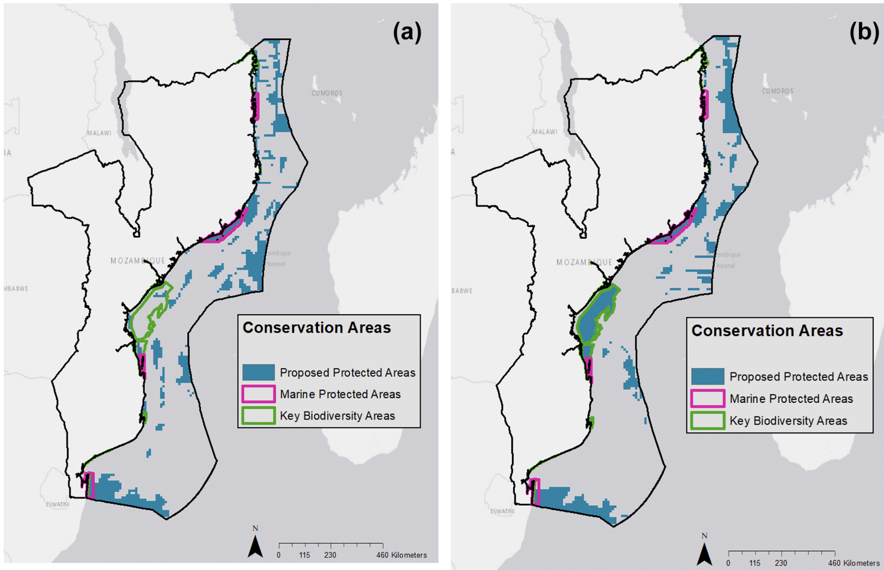

Figure 13. Prioritizr results comparing the impact of (a) not including Key Biodiversity Areas as a consideration and (b) locking-in Key Biodiversity Areas using 20% targets with combined fishing pressure as cost, no boundary penalty, and including existing marine protected areas in both results.

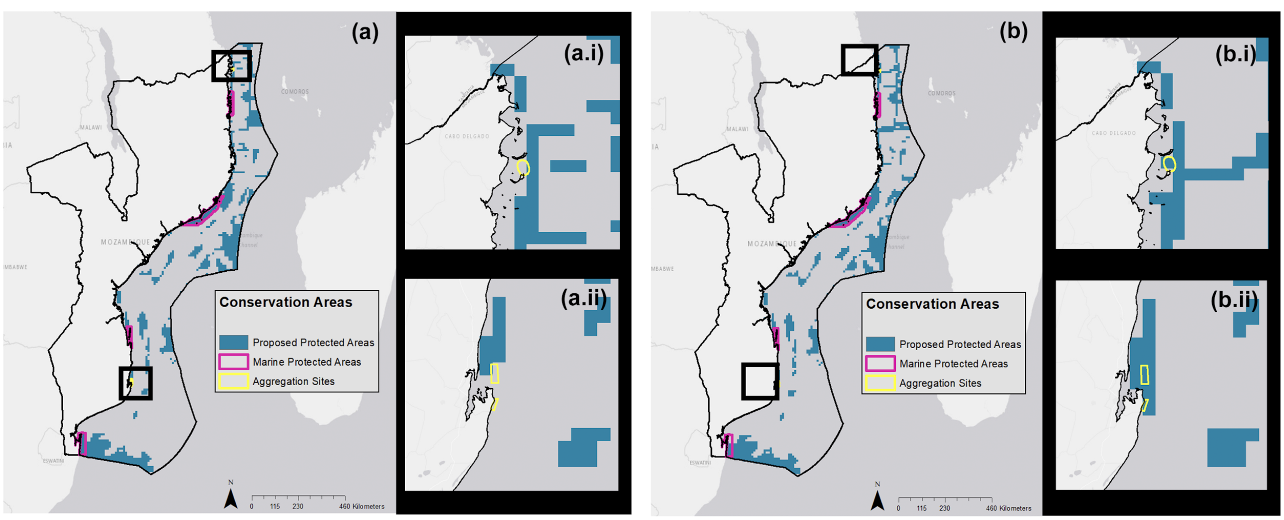

Figure 14. Prioritizr results comparing the results of (a) not including aggregation sites and (b) locking-in the aggregation sites using 20% targets with combined fishing pressure as cost, no boundary penalty, and including existing marine protected areas.

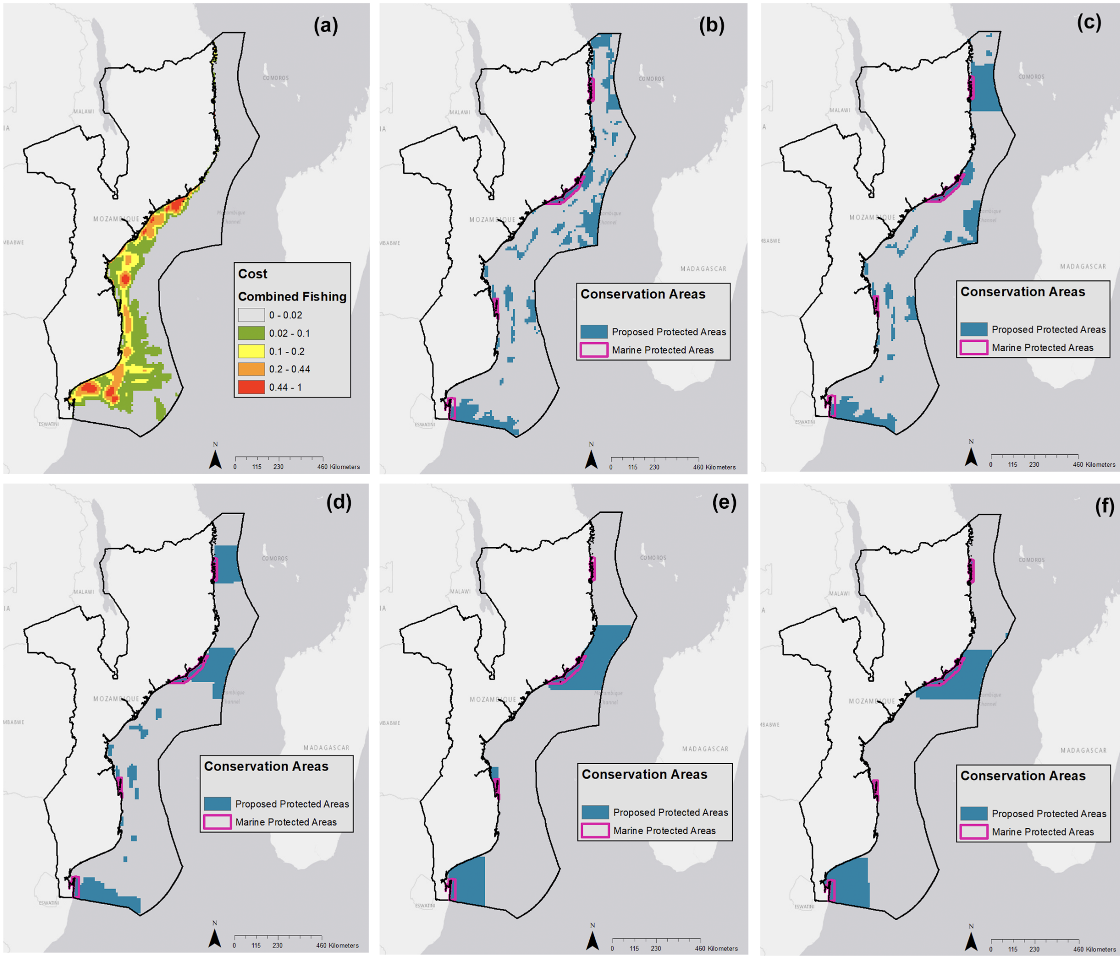

Figure 15. Prioritizr results comparing different boundary penalties using (a) combined fishing as a cost with different boundary penalties of (b) 0, (c) $1x10^{-9}$, (d) $1x10^{-6}$, (e) $1x10^{-3}$, (f) 1 with targets of 20% and including existing marine protected areas.

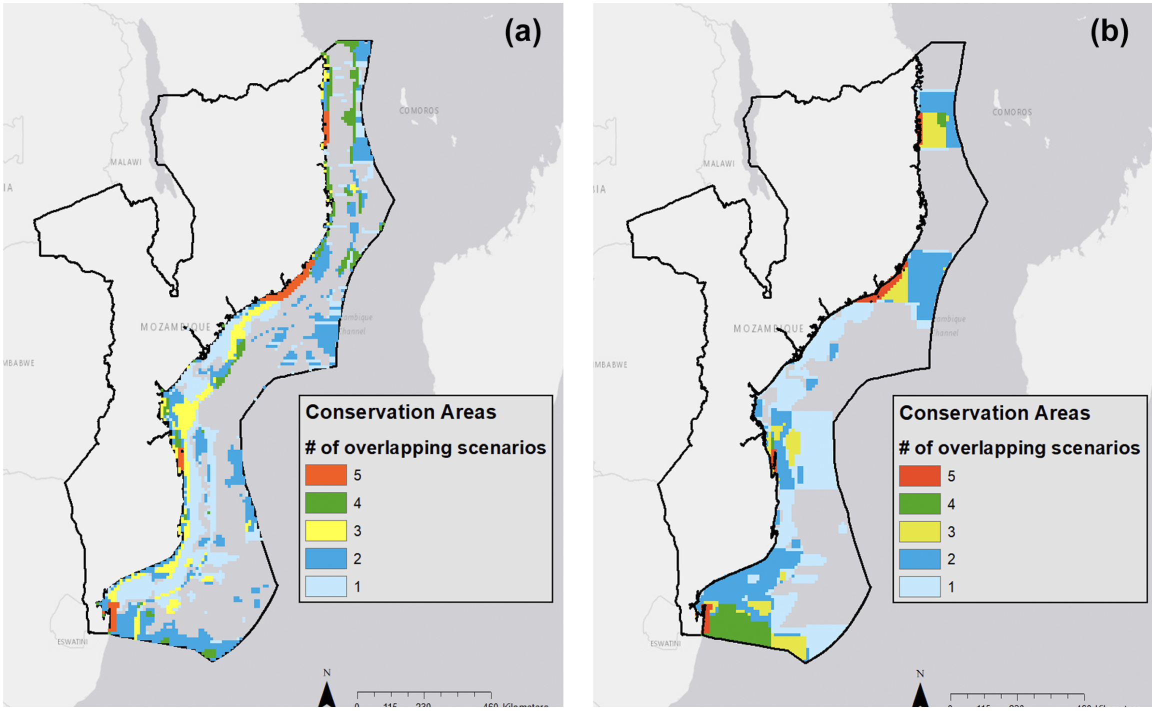

Figure 16. Comparing the number of scenarios that overlap at 20% targets with (a) no boundary penalty and (b) $1x10^{-6}$

Model

This is the repo for our project. We used the Gurobi Optimization tool to run our spatial prioritization in RStudio. Our metadata is found in the repo below.

[GitHub Repo]